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COLD WELDING RESEARCH
PHASE I REPORT

BY

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PHILCO-FORD CORPORATION
SPACE AND RE-ENTRY SYSTEMS DIVISION

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PREPARED FOR:

AIR FORCE ROCKET PROPULSION LABORATORY
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FOREWORD

This report (SKS TR-DA 1874) describes the activity accomplished during the first phase of a cold welding research program (Contract F04611-68-C-0077) during the period from May 1968 to October 1968. The project was conducted by the Philco-Ford Corporation. The Project Officers were Mr. D. T. Clift and Mr. James H. Smith. This report was prepared by Philco-Ford, Space and Re-entry Systems Division, Palo Alto, California.

This report has been reviewed and is approved.

D. T. Clift
Project Officer

ABSTRACT

The purpose of this research was to (1) study the behavior of contact resistance in air and in vacuum, and (2) determine if the stress levels on a small experimental contactor were sufficient to induce cold welding in vacuum. In each case the following metals were considered: aluminum, copper, stainless steel, and tungsten carbide. The experimental contactor is described in AFRPL Report No. AFRPL-TR-67-1 (DDC Document No. AD 380181). The experimental results show that an ion-pumped vacuum system can be success-fully employed to remove physically absorbed contaminants which would otherwise lower the probability of successful electrical contact. By analyzing high-speed motion pictures, and employing the theory of elastic deformation, it was shown that the impact forces of the contacts are high enough to deform the substrate which supports the surface oxide layer. The copper on copper contact was observed to cold weld in vacuum. Adhesion of the stainless steel and copper contact was also observed in vacuum.

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SECTION I

SUMMARY

Several tests were performed using the supplemental contactor described in
AFRPL Report No. FRPL-TR 67-1 (AD 380181) These tests included measuring
the change in contact resistance of each of the eight pairs of contacts
mounted on the supplemental contactor as the supplemental contactor was
exposed to a series of different environments. These different environ-
ments were air, vacuum (p $=$ i ^{3} torr), and vacuum in combination with
ultraviolet radiation. The test chamber was evacuated by means of ion,
sublimation and cryogenic pumps. Slow-motion movies of the supplemental
contactor's actuation stroke were made; the camera speed was usually
faster than 2300 frames per second. The velocities of impact of the contacts
were obtained from these movies. Approximate values for the stresses and
areas at the contacts' interfaces were obtained by using the theory of
elastic deformation.

The experimental results show that an ion-pumped vacuum system can be
successfully employed to remove contaminants which would otherwise lower
the probability of successful electrical contact. The results of the
analytical study show that the impact forces of the contacts are high
enough to deform the substrate which supports the surface oxide layer.

One case of cold welding was observed in vacuum. The contact involved in
the cold welding observation was copper on copper. Adhesion of the stain-
less steel and copper contact was also observed. The analysis showed
that the copper on copper couple experienced the highest ratio of impact
stress to yield stress. This suggests that the ratio of impact stress to
yield stress of contacting engineering surfaces in vacuum or space may be
an important dimensionless parameter. An "engineering surface" is
considered to be a surface which has been exposed to the atmosphere, but
has not been otherwise contaminated.

The behavior of the contacts in air was very erratic. The data usually
followed a stochastic pattern. Successful electrical contact was accom-
plished with nearly 100 percent reliability when the contactor was in
vacuum. Some changes in the contact resistances occurred in vacuum after
several hours of testing. Exposing the contactor to ultraviolet radiation
did not affect the data. When the contactor was tested in air at temper-
atures above approximately $100^{\circ}F$, there was an apparent increase in contact
resistances. Identical results were obtained in vacuum. This observed
increase was probably due, at least to some extent, to the increasing
resistance of the contactor's solenoid coil as the temperature of the
coil rose along with the ambient temperature.

SECTION II

INTRODUCTION

This report descirbes the first phase of a two-phase research project. Phase I consisted primarily of testing eight metallic contacts which were closed by a common solenoid; Phase II will be devoted to the testing of metal valves. Each of the metallic contacts consists of a pair of 1/8" diameter metal balls. The data obtained during Phase I is used to compare the performance of ion and oil diffusion pump vacuum systems. A decrease in electrical contact resistance as the ambient pressure is lowered from one atmosphere to below 10^{-6} torr is regarded as a favorable index of performance. Data describing the performance of an ion-pumped vacuum system was generated by the present project; data obtained using a diffusion-pumped vacuum system is available in Reference 1. The data obtained using a diffusion-pumped vacuum system indicates that this type of system did not effectively reduce contact resistance as the pressure was reduced several decades below 1 atmosphere. The vacuum system which was utilized during the present work was effective in substantially reducing contact resistance.

The eight contacts are mounted on a platform attached to a magnetic solenoid. The entire unit, consisting of the contacts, the platform, and the solenoid is referred to as the "supplemental contactor" or simply "the contactor". A detailed description of the design and operation of the supplemental contactor is given in Reference 1. As a result of certain difficulties which are discussed in Section III, a new supplemental contactor was built and tested. This contactor was built using spare parts furnished by TRW. Throughout the remainder of this report the rebuilt contactor is referred to as the "modified contactor". The term "original contactor" is used to refer to the condition of the contactor prior to its modification.

The contact resistances of both the original and modified contactor were first studied in air at temperatures near 32°F, 70°F, and 120°F. Later the contactor's contact resistances were studied near room temperature in vacuum ($p = 10^{-8}$ torr) and in a combined vacuum and ultraviolet radiation environment. The manifestation of cold welding (or any metal-to-metal adhesion effect), if it occurs between two contacts, is discovered from visual examination and interpretation of this data.

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1. In-Space Coldwelding Tests, R. L. Hammel, J. Rodman, R. J. Martin, TRW Systems, Summary Report, Jan. 1967, AFRPL-TR-67-1(AD 380181)

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The stress/strain conditions of the contacts over their area of impact have been studied. An analysis is included which examines the stress/strain conditions of each contact pair at its operational impact velocity in this experiment.

SECTION III

EXPERIMENTAL APPARATUS

The experimental apparatus consisted primarily of a supplemental contactor, miscellaneous supporting equipment required to monitor and control the supplemental contactor, an ion-pumped vacuum system, an ultraviolet lamp, and photographic equipment. Each of these items will be described individually.

III.1 THE SUPPLEMENTAL CONTACTORS

The following three supplemental contactors were available for testing:

    No. S/N B520404
    No. S/N B520405
    No. S/N B520406

Only one supplemental contactor, Serial Number S/N B520406, was tested during Phase I. This is the contactor which previously received 72,000 actuations in a diffusion-pumped vacuum system at TRW. A photograph of the supplemental contactor in its holding fixture is shown in Figure 1. Each contact consists of a stationary ball and an opposing ball which impacts on the stationary ball. The contacting balls are 0.125 ± 0.001 inches in diameter and are made of the following metals: stainless steel, tungsten carbide, aluminum, and copper. The exact arrangement of the balls is shown in Table I. The contacts are normally open; each contact is closed simultaneously by a single solenoid. Mechanical motion is transmitted from the solenoid plunger to each of the movable balls by a flat copper-beryllium spring. In Figure 1 this flat spring can be seen extending from under a white boron nitride disk to the brass sockets holding the movable balls. An electronics package built at TRW was used to regulate the frequency of actuation; three actuation frequencies were available. The electronics package was also used to generate an output voltage signal which was an indication of the amount of charge passing through a contact during each actuation cycle. The voltage output of the electronics package was monitored by a recorder. The recorder readings were normalized with respect to a short circuit condition achieved by manually depressing a contact.

Sample contactor data is shown in Figures 2 and 3. This data was taken directly from a pin recorder (see Paragraph III.2.1). The data comes off the recorder from right to left. In Figure 2 none of the contacts is making successful electrical contact.

Figure 1   Supplemental Contactor in Holding Fixture

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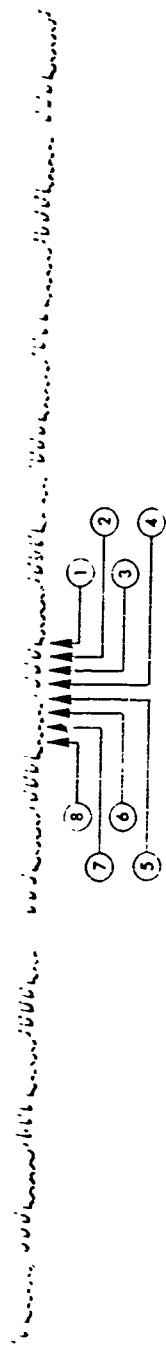
Figure 2 All Contacts Making Successful Electrical Contact
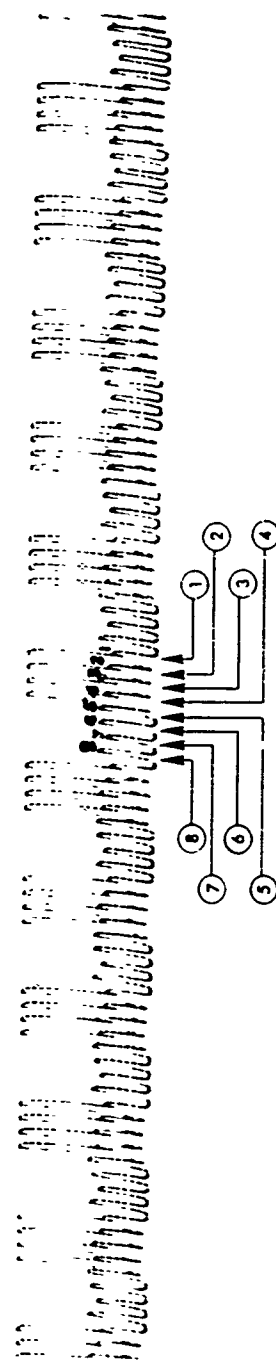
Figure 3 All Contacts Making Successful Electrical Contact

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TABLE I

TEST SUPPLEMENTAL CONTACTOR BALL ARRANGEMENT
Supplemental Contactor S/N B520406 (normally open)

Contact S_1 - 17-4 PH on 17-4 PH

Contact S_2 - WC on WC

Contact S_3 - 2014-0 on 2014-0

Contact S_4 - OFHC on OFHC

Contact S_5 - 440C on 2014-0

Contact S_6 - 440C on OFHC

Contact S_7 - 17-4 PH on 2014-0

Contact S_8 - 17-4 PH on OFHC

MATERIAL IDENTIFICATION

440C	- Stainless Steel
17-4 PH	- Stainless Steel
WC	- Tungsten Carbide
2014-0	- Aluminum
OFHC	- Oxygen Free High Con- ductivity Copper

In Figure 3 all of the contacts are making successful electrical contact; the data were obtained from one of the vacuum tests. The numbers on Figures 2 and 3 indicate the contact numbers corresponding to the position of the voltage pulses. The groups of four large pulses are not associated with the contactor data; however, they do serve to identify the voltage pulses. For example, the pulse associated with contact No. 1 immediately precedes each group of four large pulses. Figure 4 shows the result of manually short circuiting contact No. 7. The appearance of such a pulse during an actual test is indicative of cold welding. The appearance of a pulse whose height is only slightly greater than the pulses shown in Figure 3 is indicative of temporary adhesion.

Figure 4   Manual Short-Circuiting

8
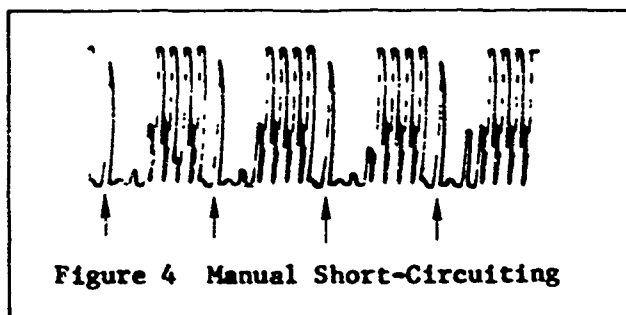
The as-received condition of contactors SN 05 and SN 06 was such that no
electrical contact between any of the eight pairs of metal balls could be
detected during actuation. In all cases electrical contact could be
detected only by manually short-circuiting a contact. Extensive work was
required to readjust the copper-beryllium spring and the gap distances
between the balls to a new configuration. The gap distance is the surface-
to-surface separation distance between an opposing pair of balls when the
solenoid is quiescent. The angular position of the upper set of balls on
contactor SN 06 (as received) was not secure. The balls attached to the
spring could be rotated approximately two or three degrees about the main
body of the contactor by the application of only about 10 gm-cm of torque.
At the conclusion of these tests on the original contactor SN 06, it was
observed that most of the balls were flattened in the region of contact.
In its as-received condition contactor SN 05 exhibited similar flattening
at its regions of contact. Several of the balls on contactors SN 05
and SN 06 were loose in their sockets, and in some cases a path traced
by a sequence of impacts could be seen on the surface of a loose ball.

Because of the difficulties listed in the previous paragraph, a new supple-
mental contactor was built using the spare parts supplied by TRW. This
contactor had a new spring and new balls and sockets. The copper-beryllium
spring was spot-welded directly to the main body of the contactor. After
removal of the original stationary brass sockets, it became apparent that
the threads in the boron nitride disk were in a marginal condition and
were not capable of supporting new brass sockets. Potassium silicate
was used to secure the position of the new stationary brass sockets. As
a result of the difficulty with the threads in the disk, contact No. 8
on the modified contactor was out of alignment by up to 0.010".
However, most of the modified contacts were aligned to within about 0.003"
as judged by visual inspection. This was at least as good as in the case
of the original contactor SN 06. Good contact between all the balls
and sockets was assured by lining the sockets with 1-mil shimstock prior
to inserting the balls. The baron nitride ceramic from the original
supplemental contactor SN 06 was thoroughly cleaned and replaced on the
solenoid. The gap distances were adjusted to produce an output voltage
pulse from the electronics package which was approximately half the height
of a voltage pulse corresponding to a short circuited contact.

It was determined that the pairs of balls on the original contractor
SN 06 were not numbered as stated in Table II of Contract FO4611-68-C-0077.
The actual arrangement of the balls on the original contactor SN 06 is
given in Table II (all experimental data are labeled according to Table I).

```
┌─────────────────────────────────────────────────────────────┐
│                         TABLE II                            │
│                                                             │
│             ORIGINAL BALL ARRANGEMENT ON SN 06              │
│                                                             │
│   S₁ was really WC x WC not 17-4 PH x 17-4 Ph               │
│                                                             │
│   S₂ was really 17-4 PH x 17-4 PH not WC x WC               │
│                                                             │
│   S₃ was really 17-4 PH x OFHC not 2014-0 x 2014-0          │
│                                                             │
│   S₄ was really 1704 PH x 2014-0 not OFHC x OFHC            │
│                                                             │
│   S₅ was really 440C x OFHC not 440C x 2014-0              │
│                                                             │
│   S₆ was really 440C x 2014-0 not 440C x OFHC             │
│                                                             │
│   S₇ was really OFHC x C∙HC not 17-4 PH x 2014-0          │
│                                                             │
│   S₈ was really 2014-0 x 2014-C not 17-4 PH x OFHC        │
└─────────────────────────────────────────────────────────────┘
```

III.2 SUPPORTING EQUIPMENT

The circuit diagram describing how the supplemental contactor was monitored
and controlled is shown in Figure 5. The terminals V1 through V4 were not
connected to any valves during Phase I. The ORS II test circuit was built
by TRW. The counter was a Computer Measurements Company frequency-period
counter (Model No. 201B); the recorder was a Beckman RS Dynograph recorder;
the stable power supply was a Hewlett Packard power supply (Model No. 721A);
and the 12-volt power supply was fabricated in the laboratory. A Missimers
combination oven and refigerator (Model FT1.5-120x350) was used to control
the temperature of the supplemental contactor during the tests in air at
32°F, 80°F, 120°F, and 150°F.

III.3 THE VACUUM SYSTEM AND RELATED EQUIPMENT

The supplemental contactor was tested in a vacuum system at a pressure of
approximately 10^{-8} torr. An AH-6 ultraviolet lamp was used to simulate
solar U.V. radiation during some of these tests. This section describes
the vacuum system, the contactor holding fixture, and the AH-6 lamp.

III.3.1 The Vacuum System

The vacuum system (Figure 6) consists primarily of a Varian VI-260 vacuum
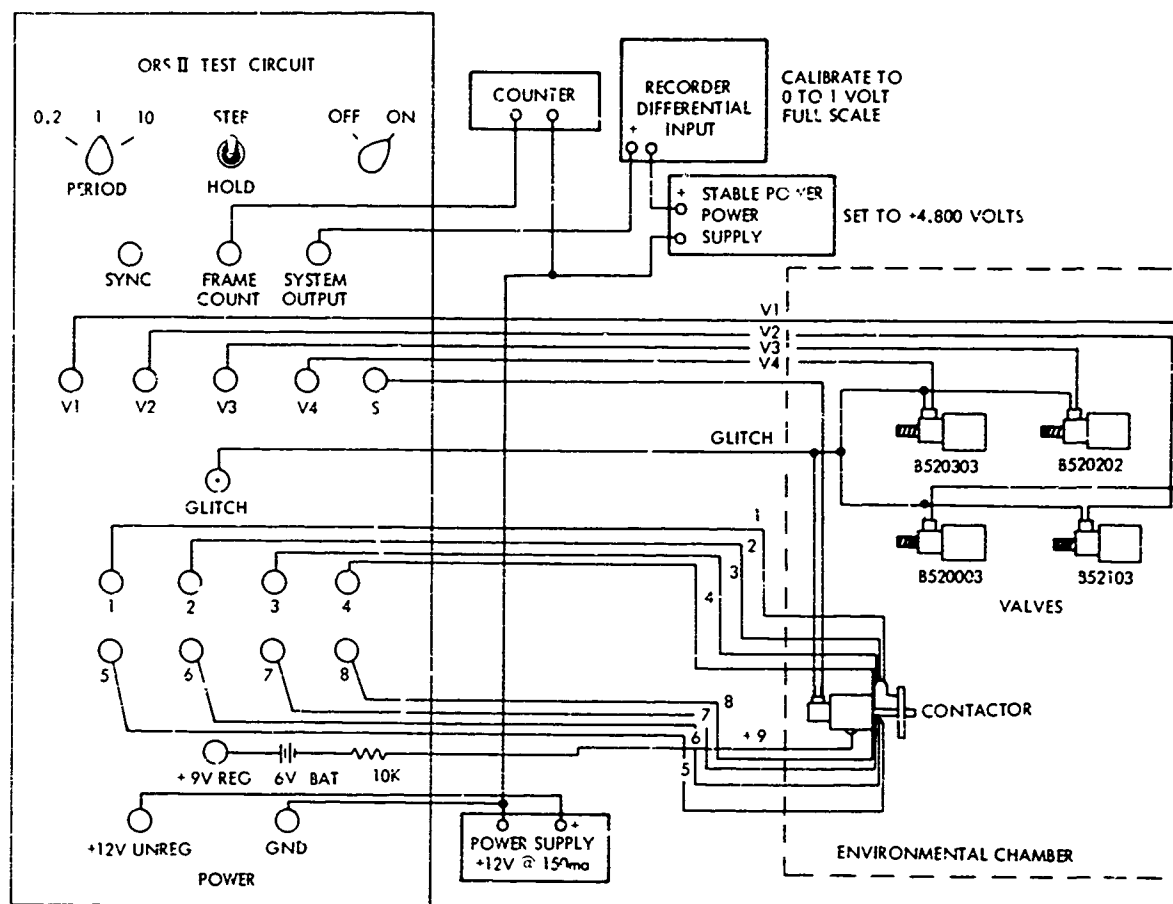system. An 18" diameter stainless steel bell jar is sealed to the original

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Figure 5 Block Diagram of Cold Welding Experiment
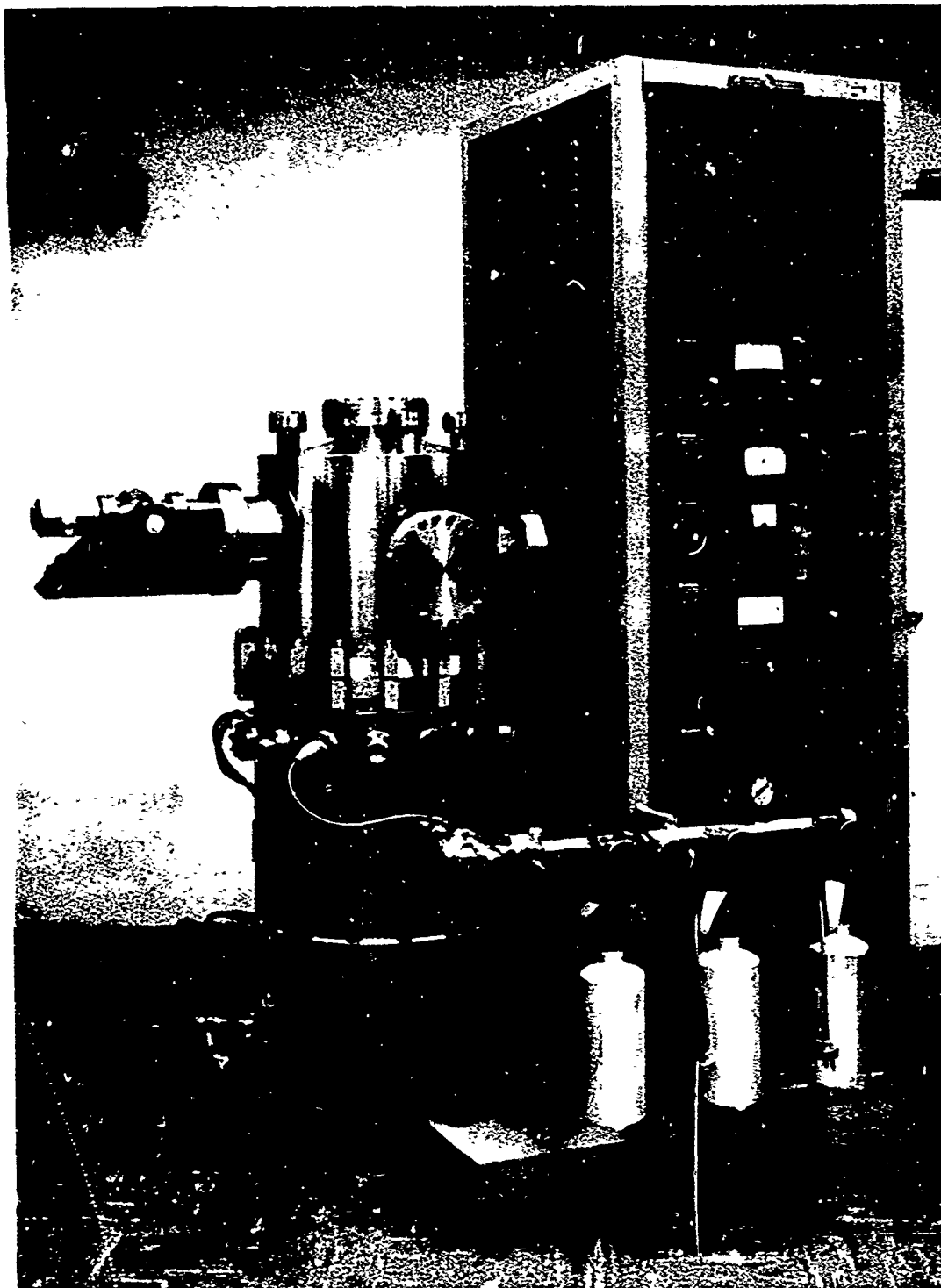
11

Figure 6   Varian VI-260 Vacuum System

VI-260 system by means of a copper gasket. The pumps used in the VI-260 vacuum system are as follows:

1. One 500 l/s VacIon pump and control unit (Varian Model 921-0038)

2. One 8000 l/s titanium sublimation pump (Varian Model 922-0032)

3. Three VacSorb 78°K cryogenically activated roughing pumps

All pressure measurements were made using a nude ion gauge(Varian No. 971-5008). With the exception of one completely dry rubber O-ring in the ion pump isolation valve, the vacuum system is all metal. The single remaining O-ring could have been removed but this would have introduced additional contamination. Without use of the ion pump isolation valve, it would not have been possible to prevent air at a pressure of one atmosphere from entering the ion pump. The contaminates contained in this air would have been re-emitted into the test chamber during a test. Initial favorable test data obviated removal of the O-ring in the isolation valve.

III.3.2 The Supplemental Contactor Holding Fixture

The supplemental contactor holding fixture is shown in Figures 1 and 7. The necessary contactor electrical leads and two copper-constantan thermocouples were introduced into the vacuum system through two 2-3/4" O.D. Conflat flanges. The contactor supporting tube was made of 304 stainless steel and the insulation of the contactor lead wires was made of fiberglas. (The insulation shown in Figures 1 and 7 is Teflon.) The large flange is a 8" O.D. Varian Conflat flange; the flange's copper sealing gasket is also shown in the figures. The rotary motion feedthrough device, Varian Model No. 954-5026, is shown at the top of Figure 7. This unit does not penetrate the wall of the vacuum system; motion is transmitted into the interior of the system by means of magnets. The rotary motion feedthrough is driven by a 1/12 RPH Haydon timing motor (Model No. E15450). This motor was activated only during the tests involving the use of ultraviolet radiation; in this case only it was necessary to rotate the main body of the contactor to insure uniform irradiation of the individual contacts.

III.3.3 The Ultraviolet Simulation Equipment

The ultraviolet simulation equipment is shown in Figure 8. The upright object is a Kovar and Quartz finger that extends sideways into the vacuum system. The AH-6 mercury lamp, which remains external to the vacuum system, is shown in the foreground. This lamp is water cooled. Figure 9 shows a comparison of Johnson's curve and a typical spectrum of the AH-6. As seen from the contactor, the water jacketed AH-6 lamp without filtering provides a source intensity equivalent to about 3 earth suns. During the experimental tests the output of the AH-6 lamp was attenuated by a neutral density filter to an intensity of about three quarters of an earth sun. It was necessary to use this filter in order to avoid overheating the contactor.

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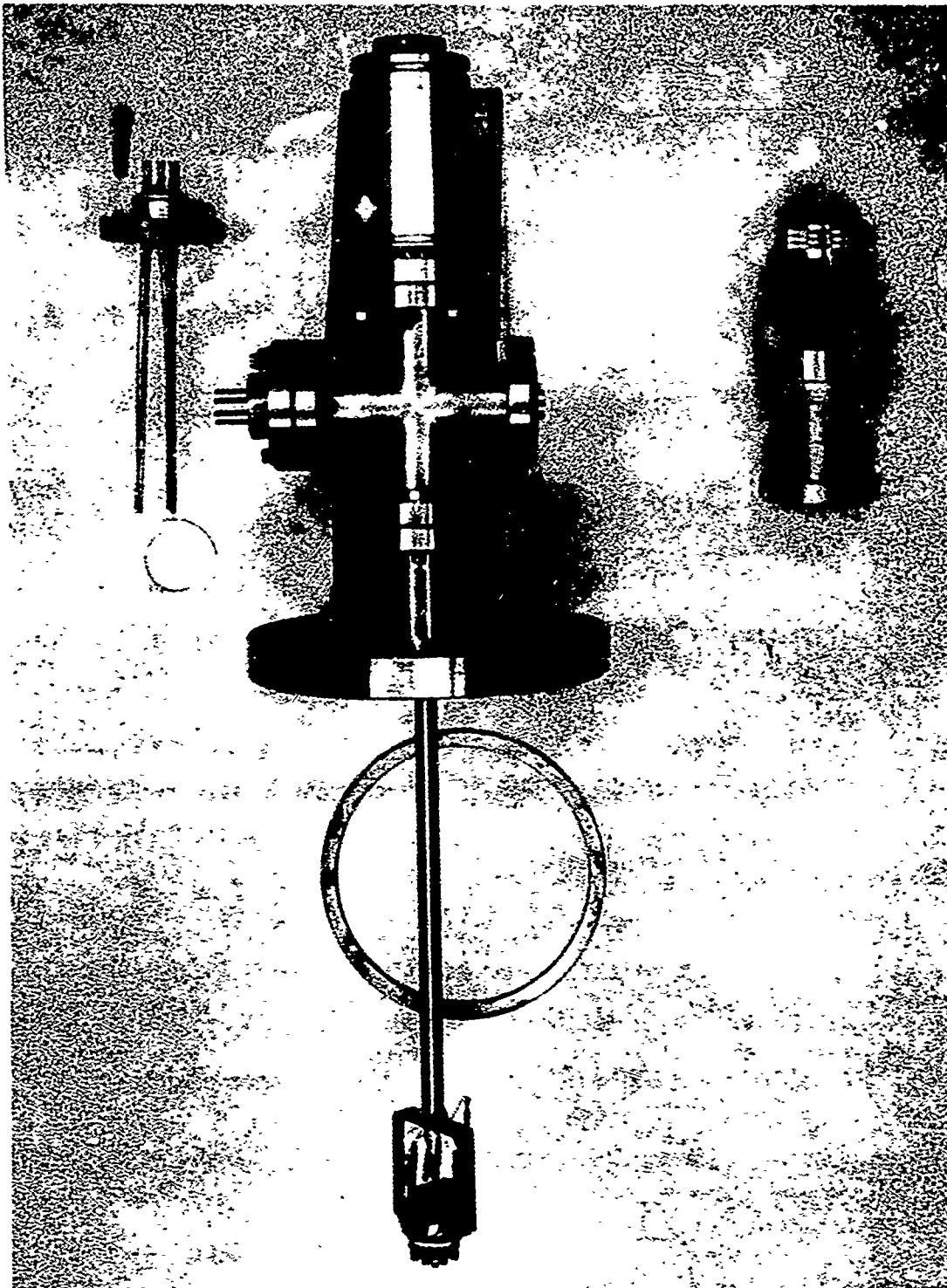
Figure 7 Supplemental Contactor Holding Fixture

Figure 8   The Ultraviolet Radiation Equipment

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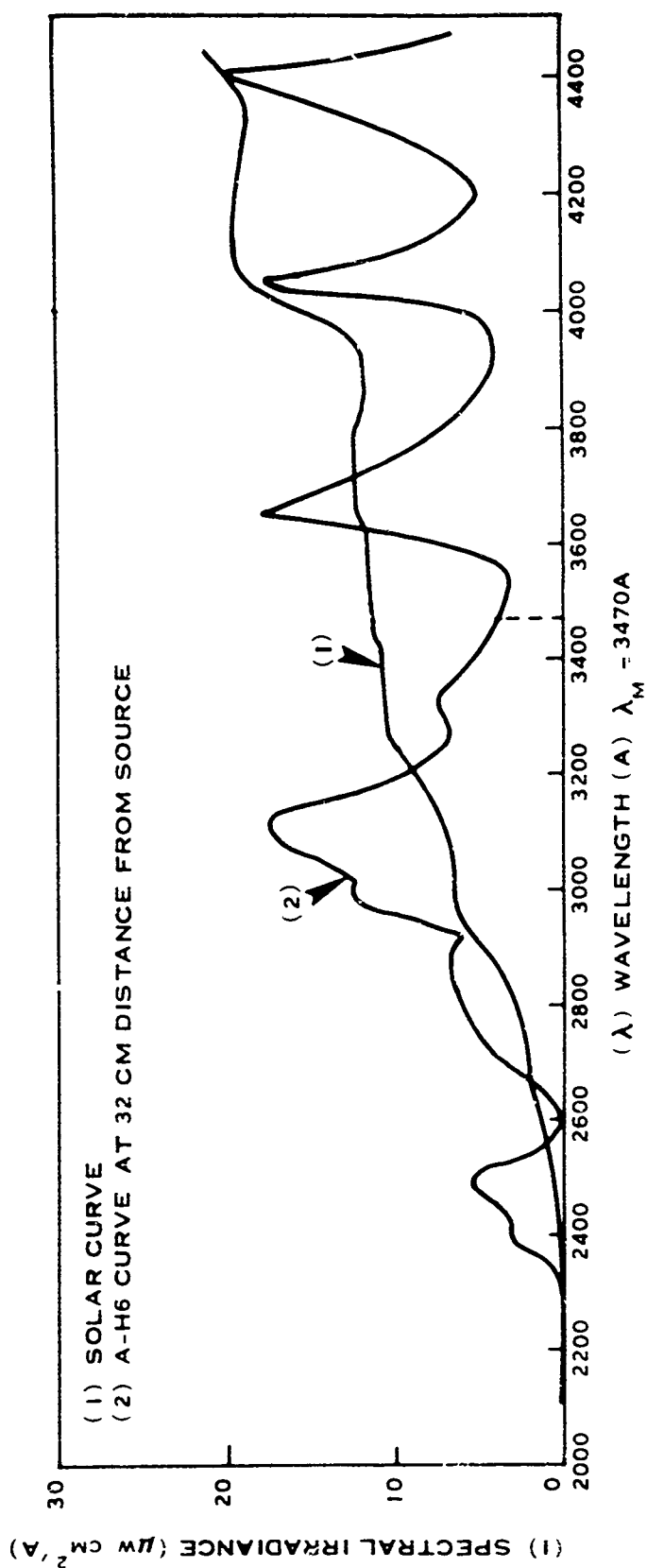
Figure 9 Spectral Energy Distribution of A-H6 Lamp and Sunlight. Data applies to radiation emitted through 1.55 mm of water and 2.5 mm of drawn quartz. (From GE Bulletin F-N412, 402M4-57, see **Table I.**)

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For reasons discussed in Paragraph VI.1.1.10 it was considered unnecessary to calibrate the AH-6 lamp.

III.4 HIGH SPEED MOTION PICTURE APPARATUS

A high-speed Hycam camera, Model No. K20S4E115, was used to take motion pictures of the actuating contactor. This camera has a maximum film speed of over 2500 frames per second. The speed of the film was measured to an accuracy of greater than 50 parts per million by a timing light which appears in the margin of the film reel. This timing light is not visable when the movies are projected on a screen. Kodachrome II 16 mm color movie film was used. All of the events of interest were spliced onto one roll of film which is enclosed with this report. The velocities of the impacting spheres were measured directly from the movie film (see Subsection V.4) by using a seven power Bausch and Lomb calibrated lens scale and a forty power Micro-Mike calibrated lens scale. The resolutions of these instruments are 0.05 mm and 0.0005" respectively. Immediately prior to photographing the contactor, the gap distances of each of the contacts was measured with a Gaertner cathetometer (Model No. M-1236-44); the resolution of this instrument is approximately $\pm$ 0.0005". Two 1000 watt lamps were used to illuminate the contactor. These lamps were turned on only when the camera was in operation, and infrared absorbing filters were used to protect the contactor from the heat generated by the lamps.

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ANALYTICAL CONSIDERATIONS

This section discusses the theoretical analysis used to describe the stress/
strain conditions of the contacting balls at their moment of impact. The
study obtains the area of contact, the average pressure at maximum deform-
ation, and the peak pressure (at the center of the contact area) at maxi-
mum deformation by utilizing the theory of elasticity. It is emphasized
that this analysis is only valid within the elastic limits of the metals
involved and for perfectly spherical contacts which have not been previ-
ously deformed. Each couple was considered individually and the average
pressure and contact area are plotted as a function of impact velocity
(see Section 6.2 for graphical results). Elastic stress limits and
approximate plastic on-set regions are indicated for each metal on the
graphs.

The purpose of this analysis is to show that for each of the eight couples
tested, at least one of the metals of each couple was deformed beyond its
yield point. This information is relevant to the present study in the
following way: if it is assumed that a necessary condition to effect
cold welding at an engineering interface is the occurance of deformation
beyond the yield point of one of the metals involved, then the presence
of stress greater than the yield stress implies that cold welding can
occur. The basis for this assumption is that if deformation does occur,
clean metal surfaces that would otherwise be separated by surface con-
taminates could bond together. Further, if permanent deformation occurs,
the elastic relief forces are reduced.

IV.1 AREA OF CONTACT

Timoshenko (2) derives the following cross-sectional impact area radius
for two colliding spherical elastic balls:

$$a = \frac{3\pi}{4} \left[\frac{(k_1 + k_2)}{(R_1 + R_2)} R_1 R_2 P_m \right]^{1/3}$$

where

$$k = \frac{1 - \mu^2}{E}$$

μ = Poisson's ratio

E = Young's modulus

R = Ball radius

P_m = Compressive force at maximum deformation

$$P_m = n\gamma_m^{3/2}$$

where

$$n = \frac{16}{9\pi^2} \left[\frac{R_1 \, k_2}{(k_1 + k_2)^2 \, (R_1 + R_2)} \right]^{\frac{1}{2}}$$

$$\gamma_m = \left[\frac{5}{4} \frac{v^2}{\pi n_1} \right]^{2/5}$$

v = impact velocity

$$n_1 = \frac{1}{m_1} + \frac{1}{m_2}$$

m = ball mass

IV.2 ELASTIC-PLASTIC TRANSITION REGIME

The average pressure (stress) over the impact area at maximum deformation is:

$$\overline{S_m} = \frac{P_m}{\pi a^2}$$

Timoshenko shows that the peak pressure at the center of the area of impact is simply $(3/2)\ \overline{S_m}$. Data on the compressive yield points, Young's moduli, and Poisson's ratios generally come from References 3 and 4 and are indicated on the graphs in Section VI.2.

A number of simplifying assumptions have been introduced in locating the plastic transition region. Tabor (5) presents the following plot of the average pressure, P_m, vs. load for an idealized couple of perfect geometry (Figure 10).

2. S. Timoshenko and J. N. Goodier, Theory of Elasticity, McGraw-Hill, 1951. Chapter 13.
3. Metal's Handbook, Vol. 1, 8th Ed., American Society for Metals, Oh'.o, 1961.
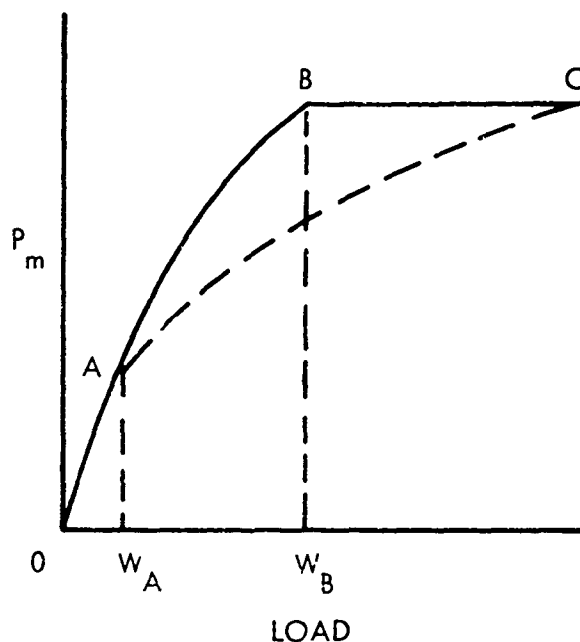
Figure 1. Average Pressure Vs. Load

Section OA is the elastically deformed region, BC the plastic region, and AB a transition zone. The non-elastic transition occurs at a load of W_A when (2)

$$P_m = 1.16Y,$$

Y being the yield strength of the material. The Section BC may also be approximated (6) from the hardness of the annealed material by

$$P_m = H$$

where

$$H = 3Y \text{ to } 4Y.$$

The numerical results indicate that the operational impact velocities throughout this experiment are in all cases sufficiently high to guarantee that at least one metal of each couple is deformed beyond its yield point. (see Section VI.2)

4. Standard Handbook for Mechanical Engineers, McGraw-Hill, New York, 1967.
5. D. Tabor, The Hardness of Metals, Clarendon Press, Oxford, England, 1951.
6. R Holm, Electric Contacts Handbook, Springer-Berlag, Berlin, Germany, 1958.

SECTION V

PROCEDURE

V.1   THE AIR TESTS

The air tests consisted of two series of three tests each. The contactor
was actuated at a frequency of 158 actuations per minute, and each test
lasted approximately six hours. The first series of air tests were performed
immediately after final check-out of the original contactor. These air tests
were performed prior to the vacuum testing of the original contactor. The
final series of air tests, which involved the modified contactor, were per-
formed at the conclusion of Phase I, i.e., after the vacuum and ultraviolet
radiation tests.

Initially it was planned to test the original contactor in air at tempera-
tures of $32^\circ F$, $70^\circ F$, and $150^\circ F$. However, when the temperature of the
original contactor reached $120^\circ F$, all of the eight contacts ceased to make
successful electrical contact. For this reason original contactor data were
not taken at a temperature higher than $120^\circ F$.

The air tests using the modified contactor were performed at temperatures of
$32^\circ F$, $80^\circ F$, and $150^\circ F$. The test originally scheduled for $70^\circ F$ was replaced
by an $80^\circ F$ test after it was determined that it was not possible to lower
the temperature of the contactor below $80^\circ F$ when it was in the vacuum system
and exposed to ultraviolet radiation. It was believed to be desirable to
test the contactor at the same temperatures in air and in vacuum.

V.2   VACUUM TESTS

Two tests were performed in vacuum in the absence of ultraviolet radiation.
In each case the contactor was held in the holding fixture. The contacts
were cleaned with alcohol immediately before the tests. One twenty-four
hour test was performed using the original contactor, and the other test,
using the modified contactor, was approximately fifty hours long. In each
case the contactor was initially actuating in an ambient atmosphere; the
pressure was lowered to below 10^{-6} torr in approximately one-half hour.
The actuation frequency was always 158 actuations per minute. During the
original contactor test the actuations were stopped after seven hours and
resumed seventeen hours later. The test of the modified contactor was ex-
tended to a length of fifty hours because the contactor data did not stabilize
during the early part of the test. The temperature of the main body of
the contactor was measured by means of the copper-constantan thermocouples
during each test. The pressure in the vacuum system, as measured by the
nude ion gauge, was maintained in the 10^{-8} torr range by operating the
titanium sublimation pump on a 5% duty cycle.

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V.3　VACUUM AND ULTRAVIOLET RADIATION TESTS

The procedure associated with subjecting the contactors to a combined vacuum
and ultraviolet radiation environment was similar to the procedure described
in Subsection V.2. The frequency of actuation was always 158 actuation per
minute. Again the original and modified contactors were tested. One test
was performed using the original contactor, and a series of two tests were
performed using the modified contactor.

At the beginning of all three tests the contactor was initially actuating
at 158 cycles per minute in an ambient atmosphere inside the vacuum system;
the pressure was reduced to below 10^{-6} torr in approximately one-half hour.
The output of the AH-6 lamp was attenuated to about three-quarters of an
earth r ⁻ a neutral density filter. The output of the AH-6 lamp was not
calibrated; the reasons for this are stated in Section 6.1.1.10.
The UV lamp and the neutral density filter were external to the vacuum
system; the attenuated UV radiation was transmitted into the vacuum system
through a quartz window.

V.3.1　Combined Environments Tests Using the Original Contactor

In order to prevent the AH-6 lamp from heating the original supplemental
contactor, a water-cooled shroud was placed around the contactor. The
shroud consisted of an open-ended copper cylinder seven inches long and
3-1/2" in diameter. A rectangular window (2" x 1") was cut in the side of
the shroud to admit the ultraviolet radiation. Water at 0°C flowed through
coils which were silver-soldered to the outer walls of the shroud. In spite
of this precaution taken to cool the contactor, the temperature of the con-
tactor rose from 80°F to 108°F after 24 hours of testing. Subsequent tests
showed that using liquid nitrogen to cool the shroud resulted in a stable
contactor temperature of approximately 80 ± 5°F. The combined environment
test of the original contactor was not repeated at this lower temperature.
The contacts on the original contactor were cleaned with alcohol immediately
before the test.

V.3.2　Combined Environments Tests Using the Modified Contactor

The modified contactor was subjected to prolonged vacuum exposure and
intermittent ultraviolet radiation exposure. These periods of ultraviolet
exposure consisted of one seven-hour period of three shorter periods of
approximately one to two hours. The sensitive controls of the AH-6 lamp
and the liquid nitrogen cooling shroud did not permit the lamp to be
operated unattended overnight.

The contacts on the modified contactor were not cleaned with alcohol prior
to testing because they had already been cleaned by previous vacuum exposure.
It was believed that not reapplying alcohol would increase the chances of
observing cold welding. The temperature of the main body of the supplemental

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contactor was less than 86°F as measured by two copper-constantan thermocouples. Liquid nitrogen was used to cool the shroud surrounding the contactor.

V.4   HIGH SPEED MOTION PICTURE PHOTOGRAPHY

Most of the film was used to photograph the motion of each of the eight contacts as the moving ball started from rest and executed one complete actuation. The contacts were photographed in pairs. A relatively small amount of the film was used to photograph the contactor when it was being actuated at 158 actuations per minute. This was the actuation frequency throughout nearly all of Phase I. The speed of the film was usually faster than 2000 frames per second.

The velocity of impact of each pair of balls was determined by measuring the separation distances of the pair of balls as a function of time. A calibrated lens scale was used to measure the separation distance of the balls corresponding to consecutive frames on the film reel. A 0.0198 ±0.0005" diameter wire which was positioned between the pair of contacts being photographed provided an accurate distance scale. The elapsed real time between each of the consecutive frames was obtained by referring to the timing light signal. The impact velocity was obtained by calculating the rate of change of the separation distance immediately before impact.

SECTION VI

RESULTS AND DISCUSSION

The analytical and experimental results are considered in two different
sections. The experimental data consists of electrical contact data and
data obtained using the high-speed motion picture camera. The analytical
results are based on the elastic theory of deformation and are presented
on eight graphs which indicate the measured impact velocities.

VI.1 EXPERIMENTAL RESULTS

The electrical contact data describe the contact resistance during the
impact of a pair of balls. A description of the recorder output is given
in Subsection III.1. The data obtained using the high-speed motion
picture camera was used to determine the velocities of impact of the balls
as described in Subsection V.4 and Paragraph VI.1.2.2.

VI.1.1 Electrical Contact Resistance Data

The electrical contact resistance data is summarized and discussed in
this section; data taken in the various environments is presented
separately in the following sections.

In air the contact resistance of both the original and modified contactors
increased substantially as the temperature of the contactor was increased
beyond approximately $100^{\circ}F$; electrical contact did not occur at temperatures
above $140^{\circ}F$. A similar increase in contact resistance also occurred in
vacuum. In all cases this temperature-dependent increase in the contact
resistance was nearly identical for all eight contacts. When the
temperature of the contactor was reduced in vacuum, the contact resistance
values returned to their initial lower temperature values; in air the
contact resistance values made a partial recovery to their lower temperacure
values. These elevated temperature effects were consistently reproducable.
This behavior suggests that the temperature-dependent increase in the
contact resistances was probably due to the increasing resistance of the
contactor's solenoid coil as the temperature of the coil rose along with
the ambient temperature.

The data taken in air using both contactors exhibited stochastic character-
istics; the data taken in vacuum did not. The modified contactor data
indicated a slightly higher frequency of successful electrical contact in
air than did the original contactor. This may have been due to the new
condition of the modified contactor's contacts or it may have been due to
the fact that the spring on the modified contactor was spot-welded
directly to the main body of the contactor. Although relatively long
term variations did occur, the vacuum data was always locally uniform from

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actuation cycle to actuation cycle. There is no evidence to suggest that ultraviolet radiation affected either the original or the modified contactor.

One instance of cold welding and one instance of adhesion were observed while testing the modified contactor in vacuum. The copper-copper couple cold-welded together intermittently during a ten minute interval after about 35 hours of vacuum exposure (p $\doteq$ 10^{-8} torr). Intermittent adhesion of the 17-4 PH stainless steel and copper couple was observed after about 73 hours of vacuum (p $\doteq$ 10^{-8} torr) exposure. This latter event occurred in the presence of ultraviolet radiation, but there is no evidence to associate the adhesion with the presence of the ultraviolet radiation. The adhesion persisted after the ultraviolet lamp was turned off. The cold welding and adhesion of the modified contactor occurred during the first test after its fabrication. This suggests that: (1) prolonged testing of a contactor gradually flattens the balls and thereby reduces the impact stresses at the contact interface, and (2) adhesion which occurs early in the life of a contact may disturb the surfaces of the contact and prevent cold welding during subsequent actuations.

The frequency of actuation was always 158 actuations per minute. Based on the high speed motion picture results, this choice of actuation frequency can be questioned. The results of the motion pictures show that the 158 cycles per minute actuation frequency does not permit the moving balls to come to rest between actuation cycles. During the satellite tests the moving balls were allowed to come to rest prior to actuation. However, the results of this experiment indicate that if this higher frequency had not been used, the very rare occurances of cold welding and adhesion might not have been observed.

VI.1.1.1 <u>Electrical Contact Data Taken in Air at 70°F Using the Original Contactor.</u> In room temperature air (70 ± 2°F) the original contactor showed stochastic behavior, i.e., the data contained statistical fluctuations but these fluctuations were not random. The frequency of electrical contact decreased after the first two or three minutes of operation; some of the contacts never closed electrically during the entire test, but in some instances achieved electrical contact several thousand actuations later during another test. It was not possible to obtain a high ratio of observed electrical contacts to actual solenoid actuations. The results are shown on Figures 11 through 13.

Each bar on Figures 11 through 13 denotes the ratio of the frequency of electrical contact to the frequency of actuation averaged over a five minute interval. Approximately 800 actuations occurred during this interval, and since the electronics package sampled every eighth actuation, approximately 100 data points are associated with each five minute interval. An electrical contact was judged to have occurred if the voltage signal from the electronics package was more than half as large as the voltage signal resulting from the successful electrical contact of a freshly cleaned pair of contacts. The data taken at t = 0.1 hour at the extreme left-hand side of the graphs were really taken during the first five minutes of continued actuation.
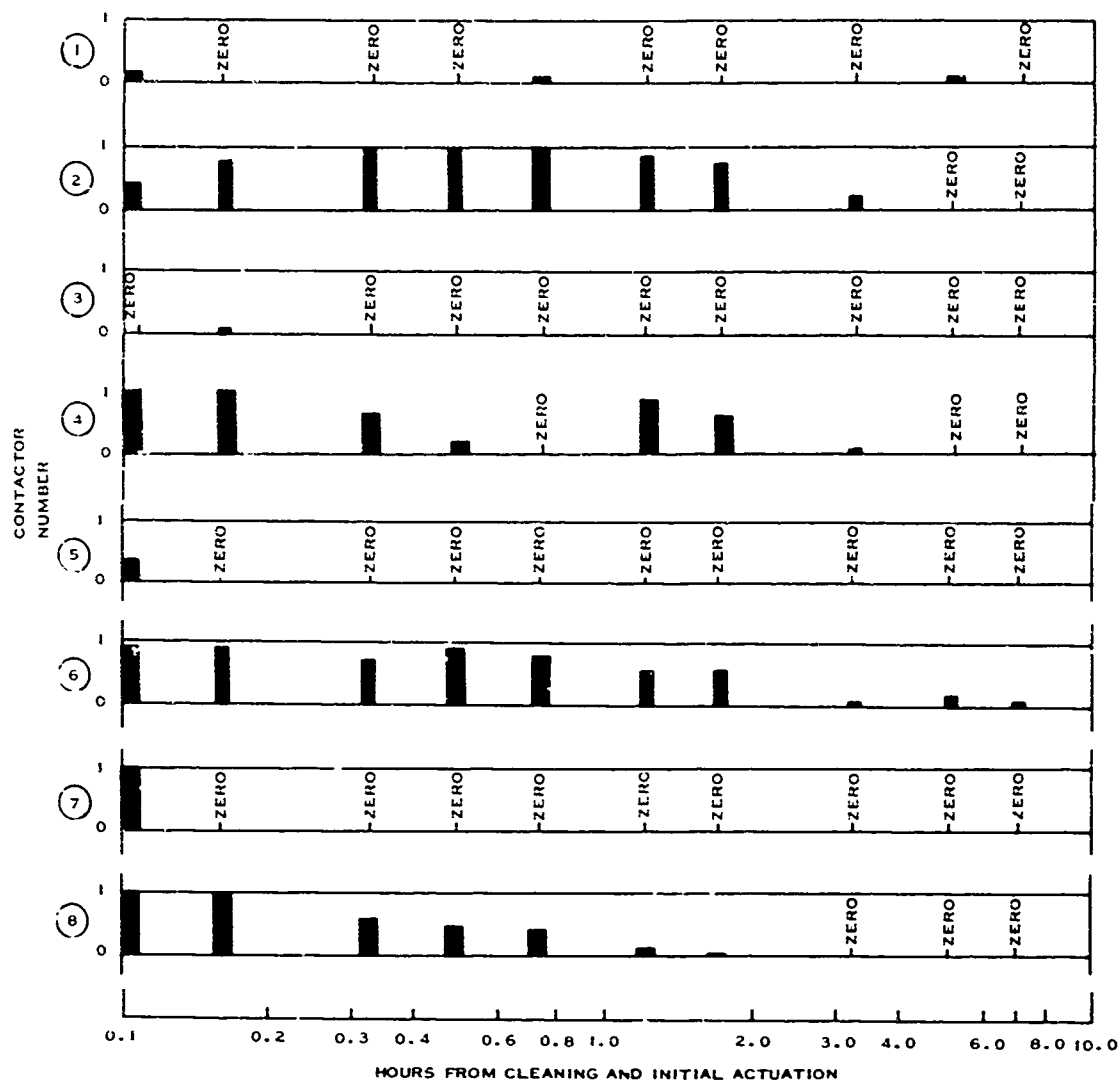
28

Figure 11 Electrical Contact Data Taken in Air at 70° F Using the Original Contactor
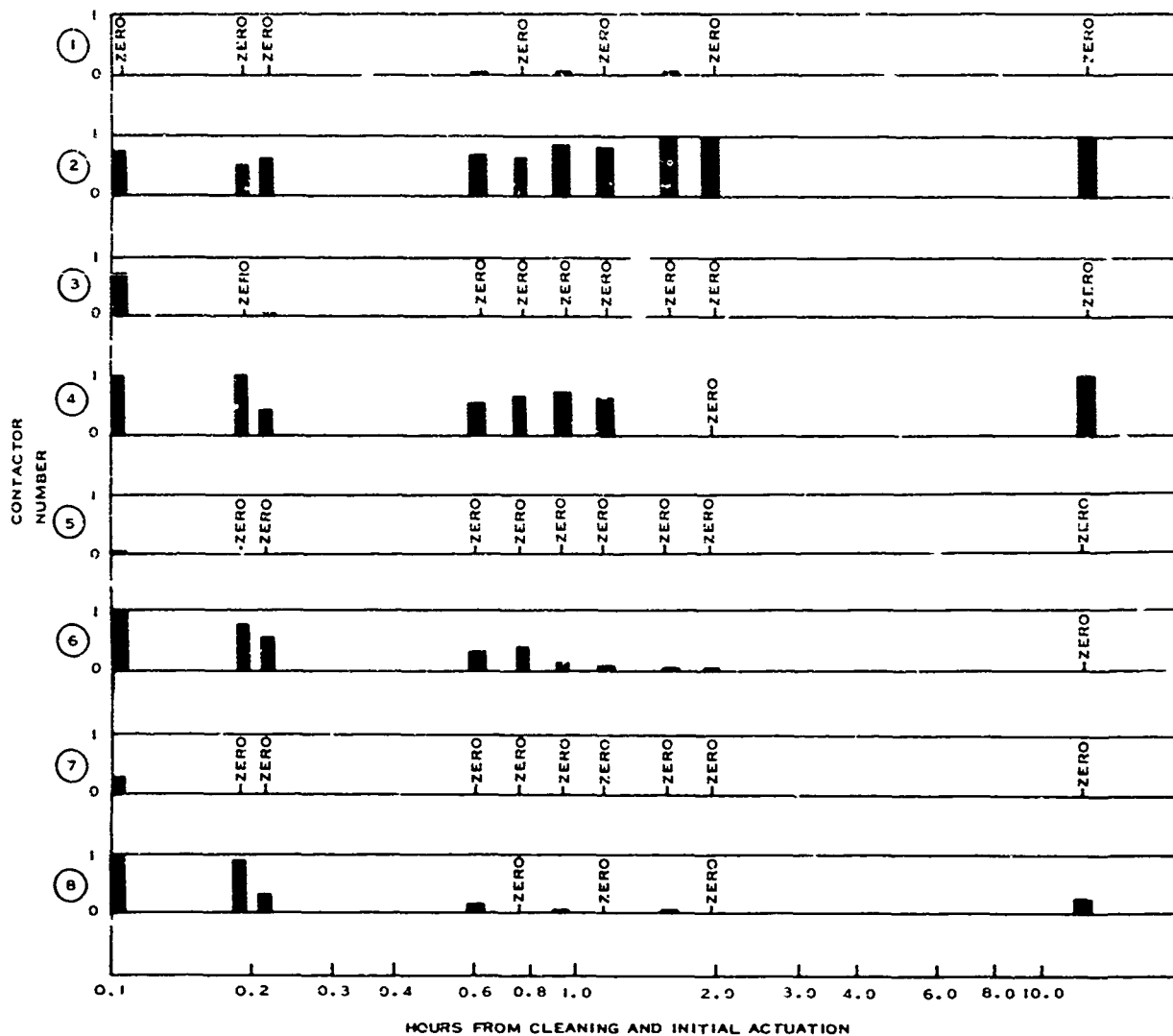
Figure 12   Electrical Contact Data Taken in Air at 70°F Using the Original Contactor
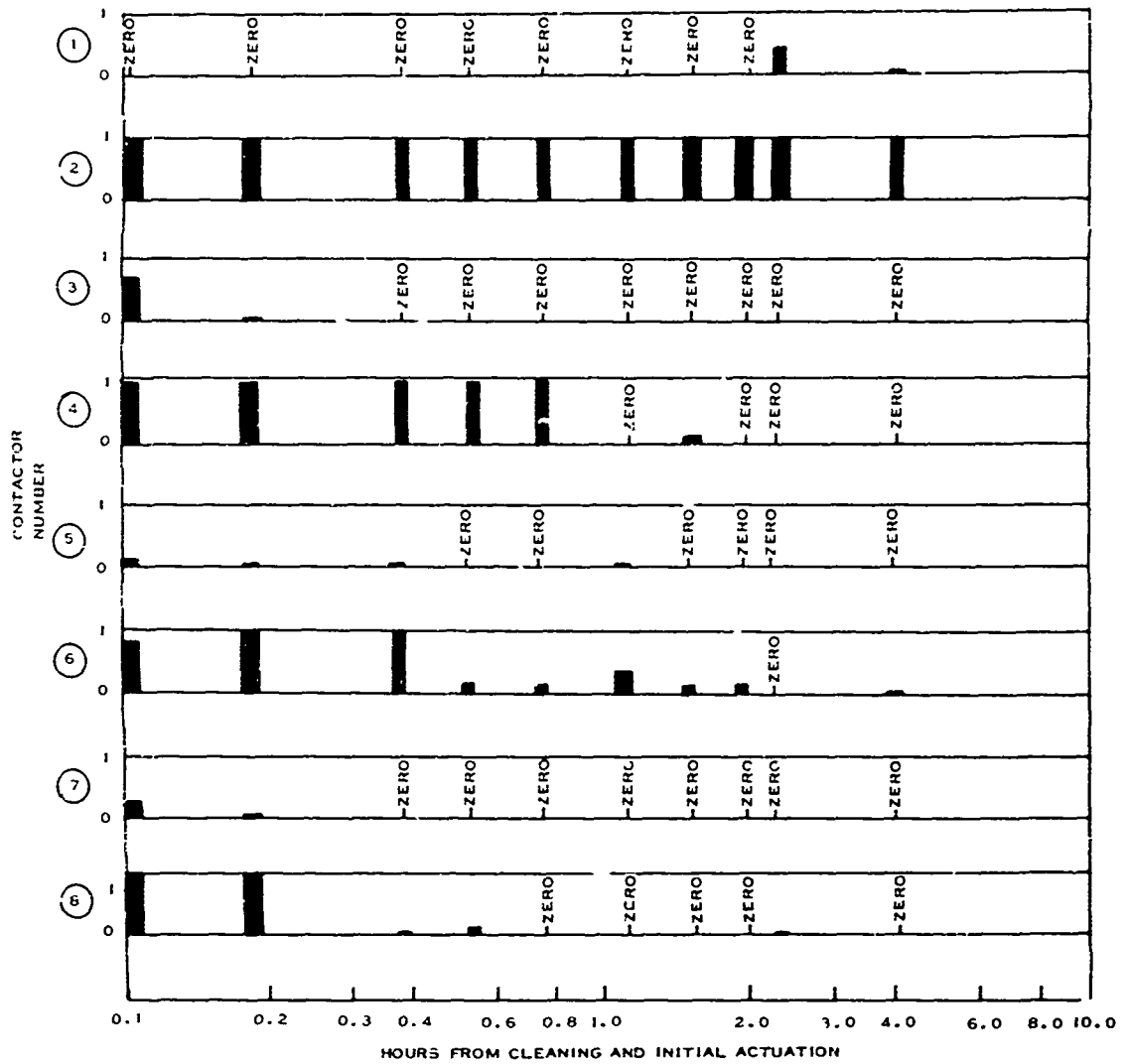
30

Figure 13 Electrical Contact Data Taken in Air at 70°F Using the Original Contactor

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Note that far fewer successful electrical contacts were made during these tests than during the TRW tests in air (Page 33, In-Space Cold Welding Tests, TRW Systems, Inc.). The likely source of difficulty is the fact that most of the metal balls were substantially flattened in the region of contact, presumably due to extensive use. This was not noticed upon receipt of the contactor since this flattening could not be observed without disassembling the contactor. However, after it became apparent that contactor 06 was making abnormally few electrical contacts in air, it was disassembled and the flattening was clearly visible to the unaided eye. It was further observed that part of the flat copper spring which presses the balls together during actuation had lost one of its small "ears" which permit the copper spring (and consequently the upper balls) to maintain correct angular alignment with respect to the lower, stationary balls. Data obtained immediately after cleaning the balls with alcohol and data obtained 24 hours after cleaning did not exhibit different trends (during the 24 hour interval the contactor was exposed to laboratory air).

VI.1.1.2 Electrical Contact Data Taken in Air at 80°F Using the Modified Contactor. The data taken in air at near room temperature (80 ± 2°F) using the modified contactor (see Figure 14) did not differ in any significant way from the data taken with the original contactor near room temperature. The data were obtained and normalized exactly like the data taken in 70°F air using the original contactor. The data taken with the modified contactor showed a slightly higher frequency of successful electrical contact. This was probably due to the facts that the modified contactor had experienced less wear prior to its test, and that the spring of the modified contactor was spot-welded directly to the main body of the contactor.

VI.1.1.3 Electrical Contact Data Taken in Air at 32°F Using the Original Contactor. The reduced data taken when the original contactor was in air at 32 ± 2°F is shown on Figure 15. The data were obtained and normalized exactly like the data taken in 70°F air. The data associated with contactor Number 3 is abnormal because of a bad connection which was repaired after the test. The data taken in air at 32°F using the original contactor shows approximately the same trends as the data taken in air at 70°F.

VI.1.1.4 Electrical Contact Data Taken in Air at 32°F Using the Modified Contactor. The reduced data taken when the modified contactor was in air at 32 ± 4°F is shown on Figure 16. The data was obtained and normalized exactly like the data taken in 70°F using the original contactor. The data taken in air at 32°F using the modified contactor shows approximately the same trends as the data taken in 80°F air.

VI.1.1.5 Electrical Contact Data Taken in Air at 120°F Using the Original Contactor. When the original contactor was in air at 120 ± 3°F, the number of electrical contacts fell to nearly zero. The results are shown on Figures 17 and 17a. The width of the bar on these graphs denotes the length of the sampling interval, and the height of the bar denotes the average value of the ratio of the electrical contact frequency to the
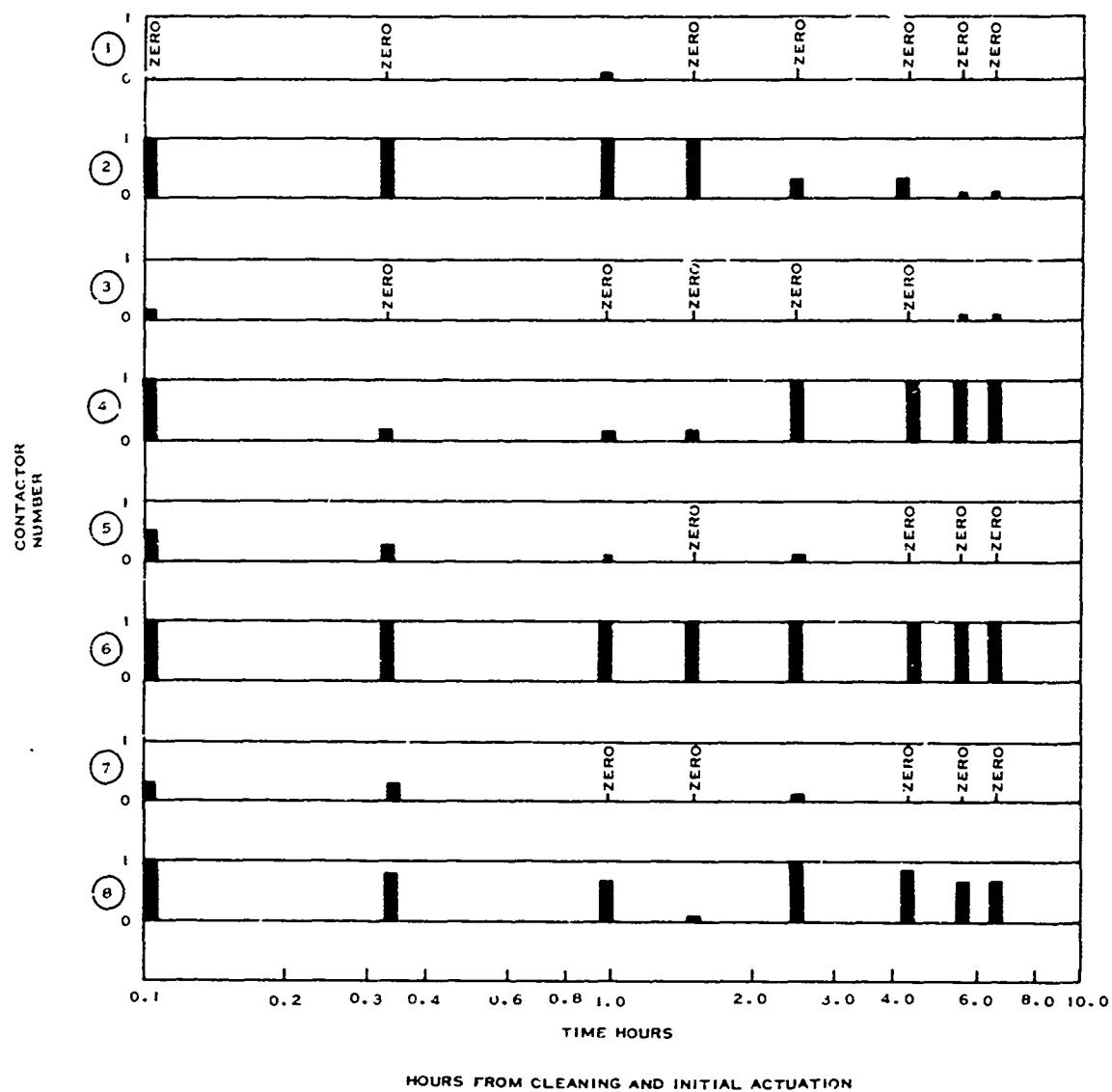
32

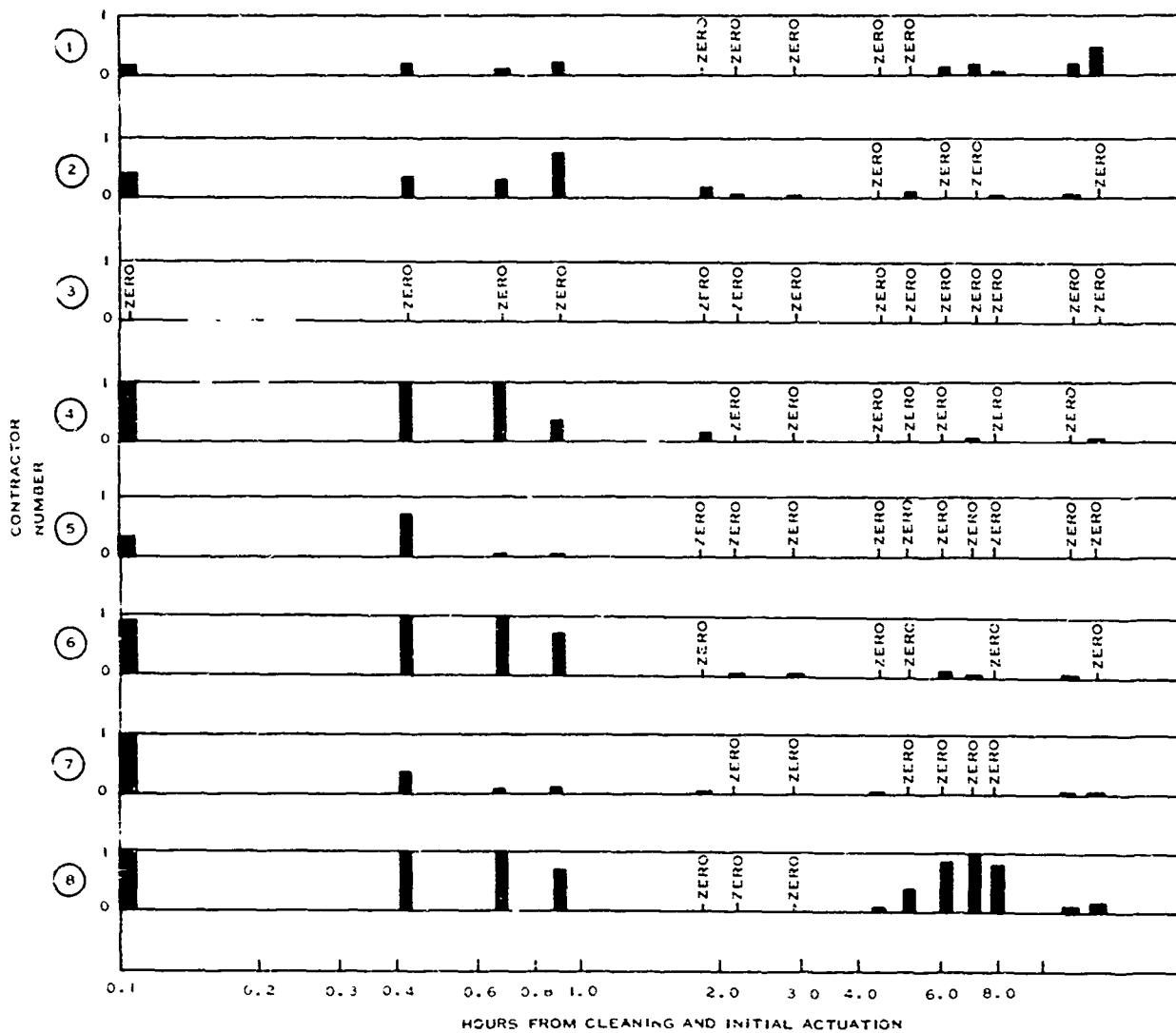Figure 14 Electrical Contact Data Taken in Air at 80^OF Using the Modified Contactor

Figure 15 Electrical Contact Data Taken in Air at 32°F Using the Original Contactor
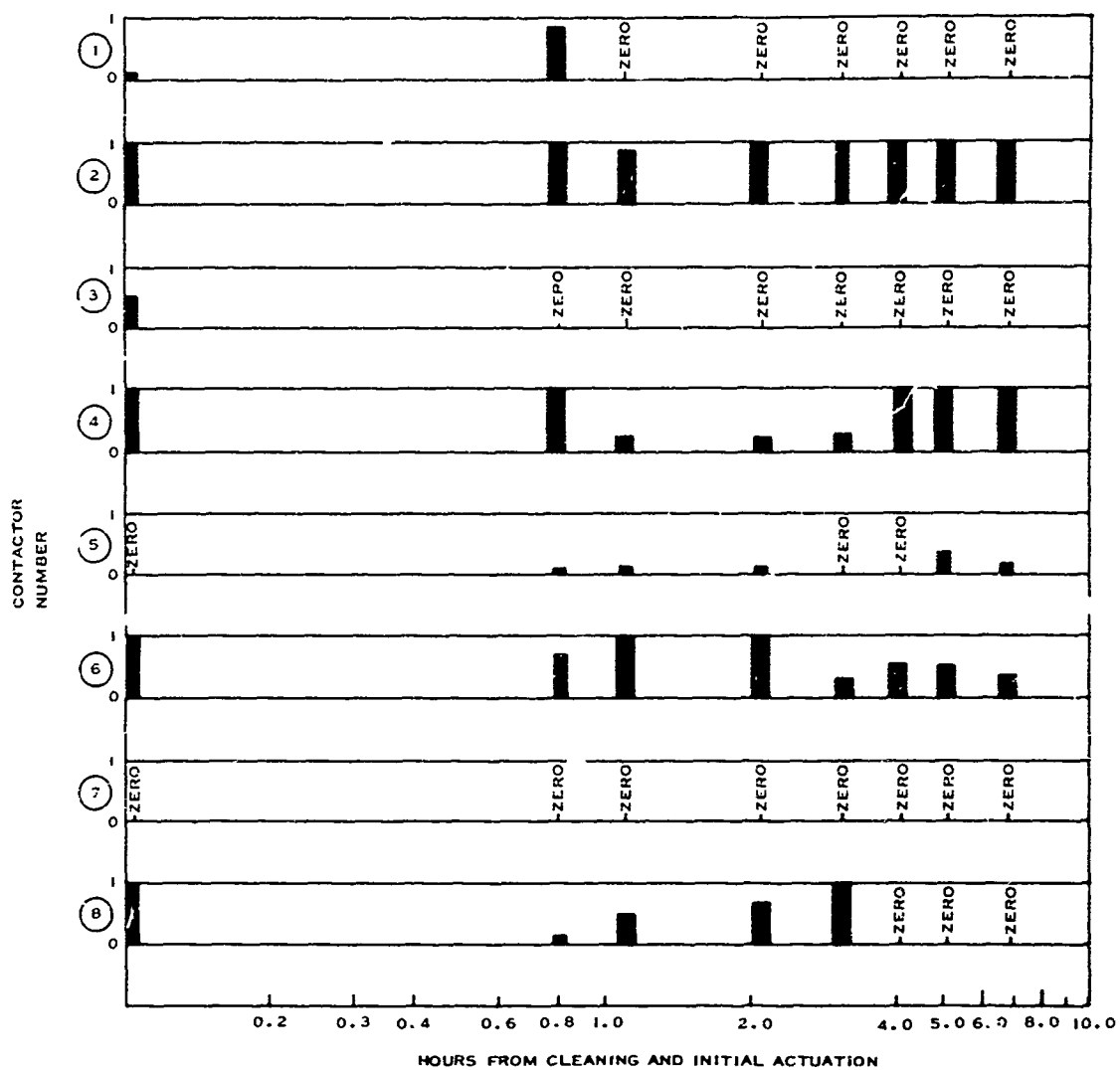
34

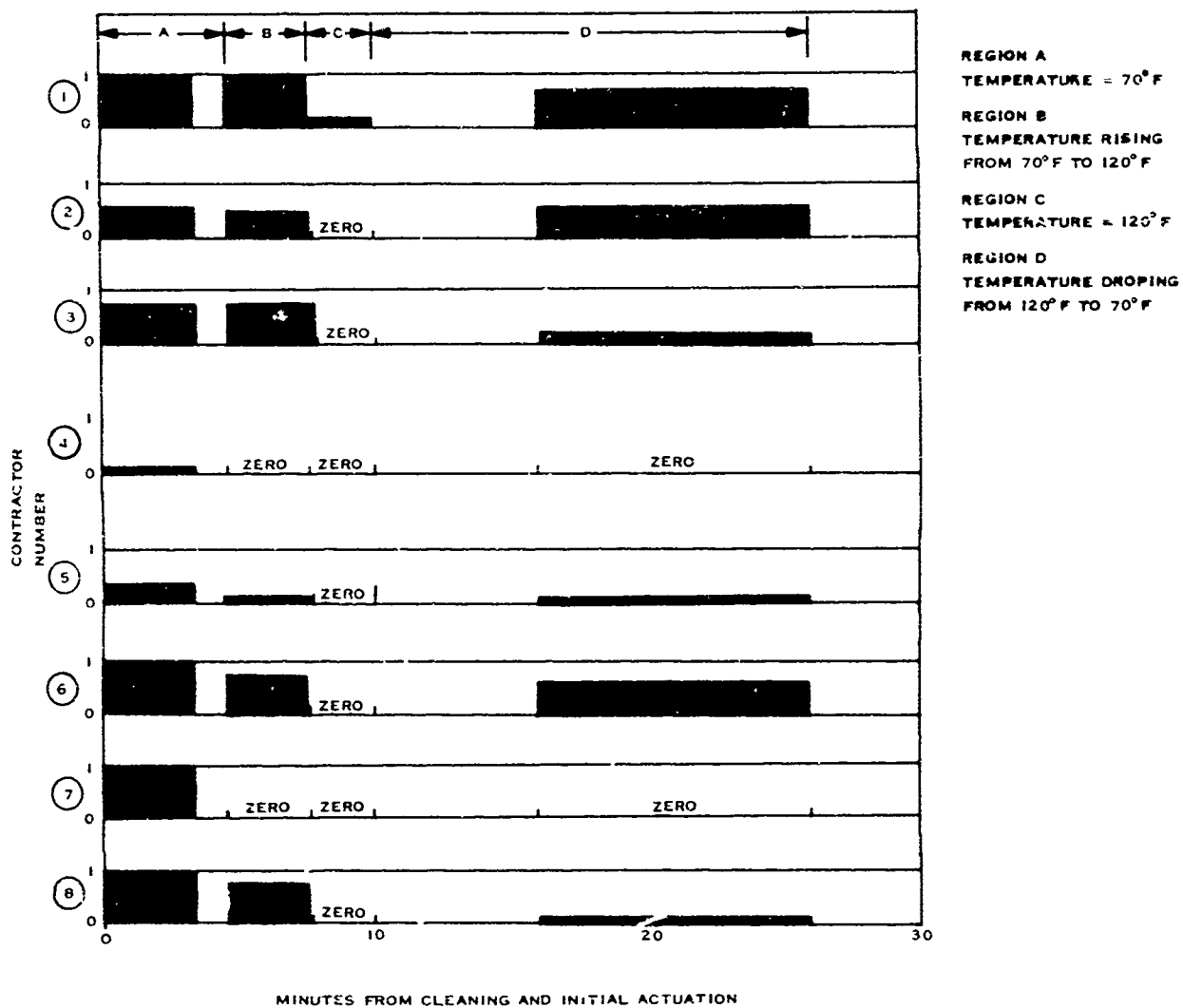Figure 16 Electrical Contact Data Taken in Air at 32^OF Using the Modified Contactor

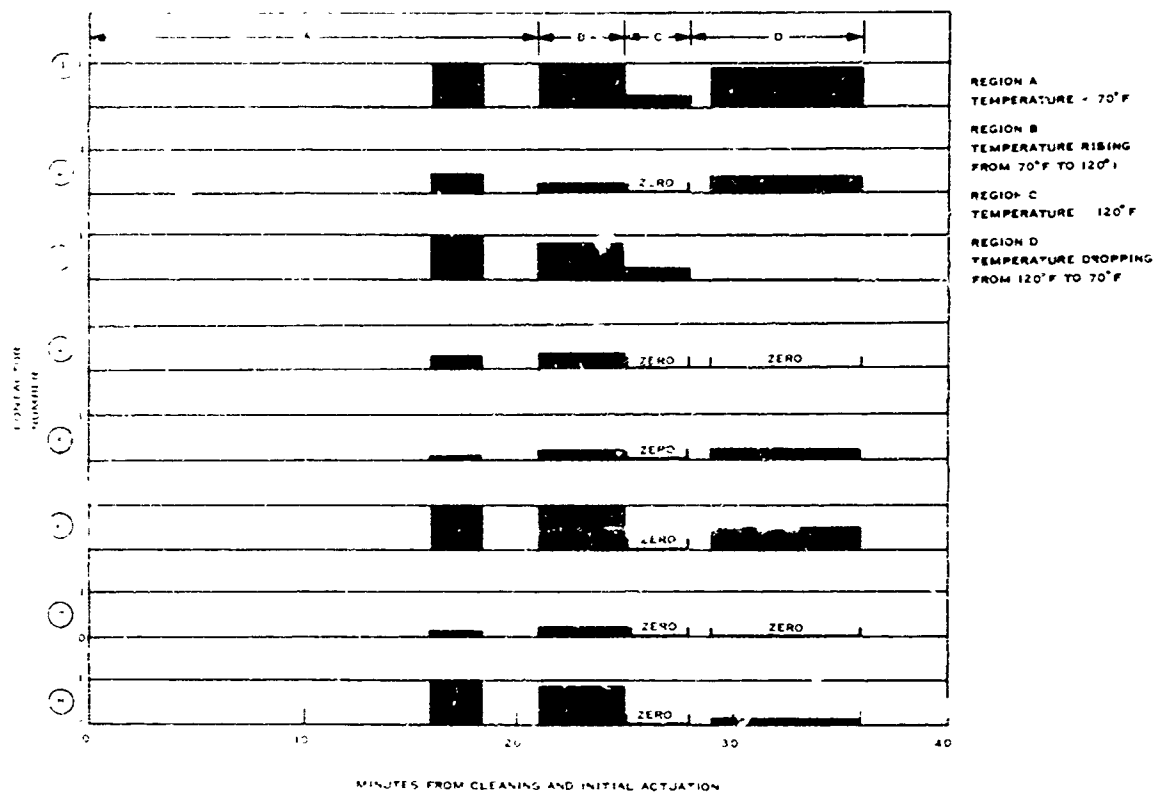Figure 17 Electrical Contact Data Taken in Air at 120°F Using the Original Contactor

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Figure 17a Electrical Contact Data Taken in Air at 120°F Using the Original Contactor

actuation frequency in the sampling interval. As the contactor was allowed
to cool back down to room temperature it was observed that the frequency
of electrical contact rose and finally returned to the values previously
observed in 70°F air.

VI.1.1.6 Electrical Contact Data Taken in Air at 15C°F Using the Modified
Contactor. The data taken in air at 150 ± 4°F indicated that electrical con-
tact does not occur under these conditions. The data taken from the
recorder was identical to the data shown in Figure 2.

Data taken in air as the temperature of the air was raised from 70°F to
149°F are shown in Figures 18 through 22. Note the diminution of the
pulse height as the temperature of the air increases. Figure 23 shows
a record obtained about five minutes after the record shown in Figure 22.
Note that the reduction in temperature to 77°F resulted in a return of the
pulse heights of contacts Nos. 2, 4, and 6 to a significant fraction of
their initial values. The accuracy of the temperature reading shown in
Figures 18 through 23 is ± 2°F.

VI.1.1.7 Electrical Contact Data Taken in Vacuum Using the Original Contactor.
After completion of the tests in air, the original contactor was tested in
vacuum. The pressure in the vacuum system was in the 10^{-8} torr range as
measured by a nude ion gauge. Earlier, when the contactor was not in the
vacuum system, a pressure of 2×10^{-10} torr was attained. It should be
noted that the temperature of the contactor in vacuum was 80 ± 5°F rather
than 70°F. This was the result of the fact that normal operation of the
titanium sublimator heated the optical baffle which shields the test area
from the sublimator. This optical baffle in turn . eated the contactor by
radiation.

The behavior of the contactor in a 10^{-8} torr vacuum was completely different
from its behavior in air at 70°F. In vacuum, electrical contact was
achieved with almost 100 percent reliability. Contact No. 3 was an
exception, it rarely indicated an electrical contact. It is assumed
its abnormal behavior in vacuum was due to a faulty connection or another
difficulty other than a surface effect. This difficulty with contact
No. 3 did not appear in subsequent tests. No instance of cold welding was
observed. Unlike the data taken in air, the vacuum data did not exhibit
stochastic characteristics. The data obtained in vacuum followed a regular
pattern which was the same from actuation to actuation. Some increase in
contact resistance after several hours of actuation was evidenced by a
slight attenuation of the electronics package's output voltage pulse, but
electrical contact was almost always made, even after 24 hours of vacuum
exposure. This is in sharp contrast to the behavior of the contactor in
air, where in several cases electrical contact was not made even immediately
after cleaning the contacts with alcohol.

The results of the vacuum test are shown on Figure 24. Each bar on the
graph expresses the ratio of the average pulse height in a five minute test
interval to the maximum pulse height observed in vacuum immediately after
actuation was begun. Unlike the bars on the graphs describing the data
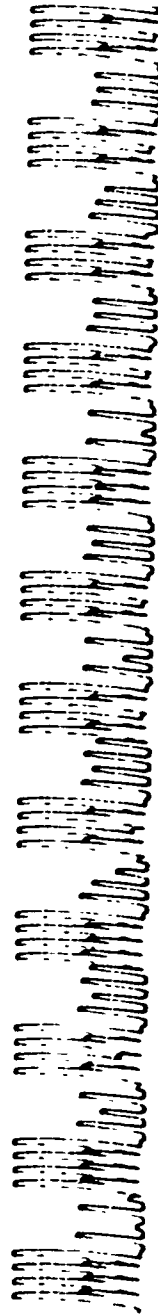
38

Temperature = 70°F

Figure 18 Electrical Contact Data Taken in Air at Elevated
Temperatures Using the Modified Contactor
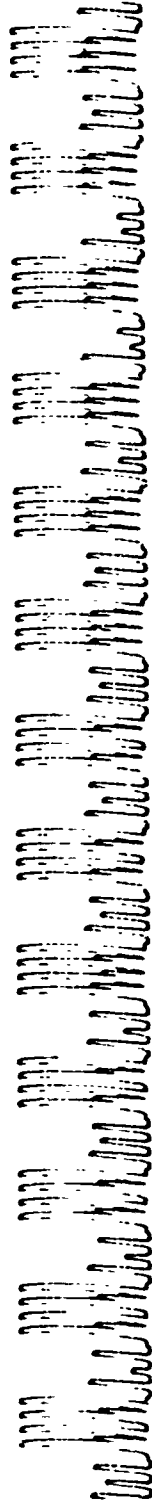
39

Temperature = 104°F

Figure 19 Electrical Contact Data Taken in Air at Elevated
Temperatures Using the Modified Contactor

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Temperature = 131°F

Figure 20 Electrical Contact Data Taken in Air at Elevated
Temperatures Using the Modified Contactor

41

Temperature = 140°F

Figure 21 Electrical Contact Data Taken in Air at Elevated
Temperatures Using the Modified Contactor
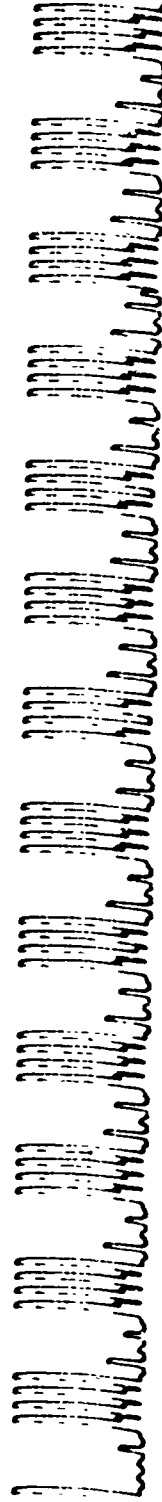
42

Temperature = 149°F

Figure 22   Electrical Contact Data Taken in Air at Elevated
Temperatures Using the Modified Contactor

43

Temperature = 77°F

Figure 23   Electrical Contact Data Taken in Air
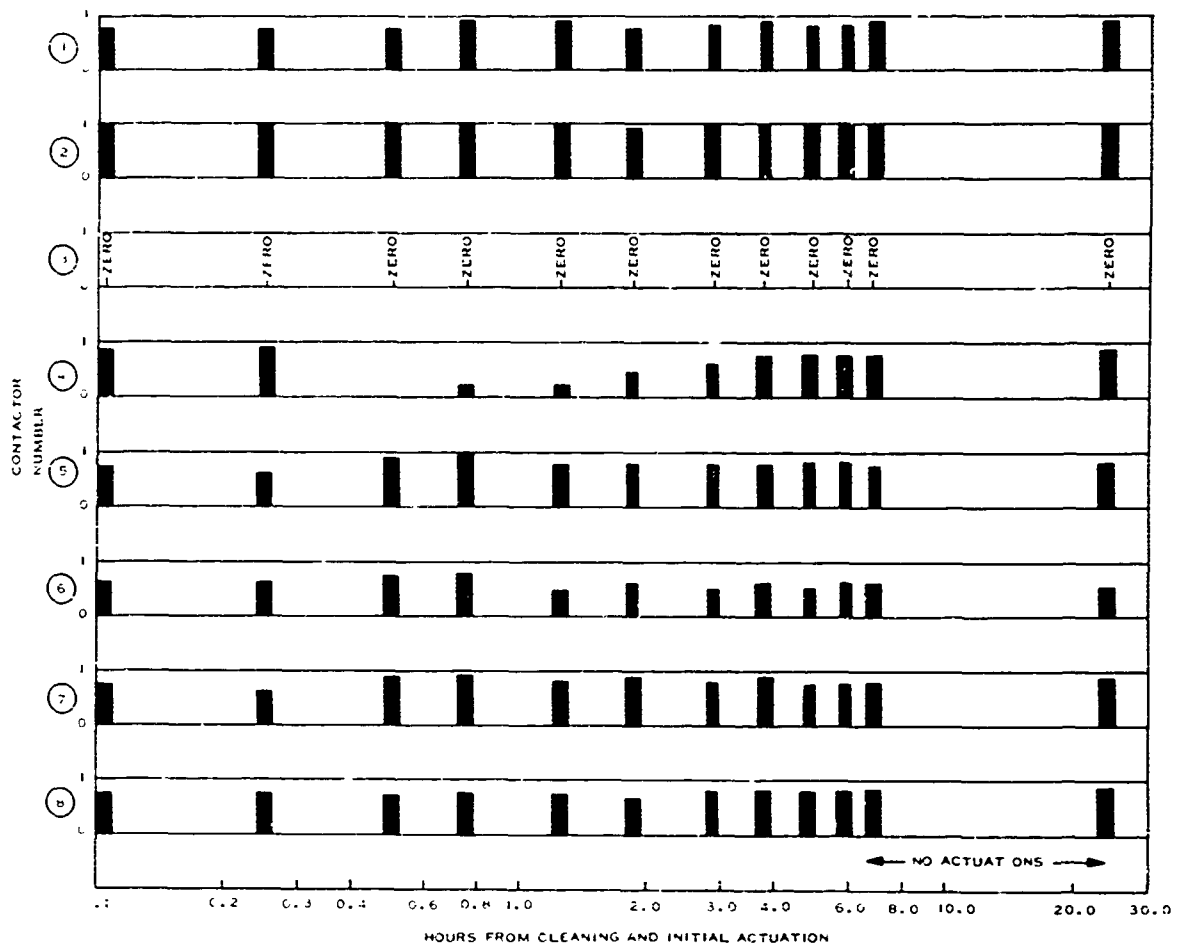Using the Modified Contactor

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Figure 24 Electrical Contact Data Taken in Vacuum Using the Original Contactor

obtained in air, the bars on Figure 24 denote an average pulse height on
the recorder and not the frequency of successful electrical contact. (In
vacuum succesful electrical contact approached 100 percent.) In the
interval between 7 hours and 24 hours the contactor was not actuated.

The electronics package's output voltage, corresponding to electrical
closure immediately after actuation was begun in vacuum, was slightly
less than this voltage during the bench tests in air. The pulse heights
on the recorder paper were approximately 7 and 9 units respectively. Based
on previous experience adjusting the contactor, it is assumed that this
discrepancy is partly due to a peculiar cross-coupling between different
pairs of contacts. When the contactor was being adjusted, it was observed
that the average pulse height denoting electrical closure decreased as
the number of pairs of contacts which were experiencing electrical contact
increased. For example, when the number of pairs of contacts producing
measurable voltage pulses was increased from four to five by adjusting the
gap distance of the fifth contactor, the average pulse height of the five
new pulses was less than the average pulse height of the four previous
pulses. The only way to maintain an average pulse height equal to approx-
imately half that of the pulse initiated by a short circuit was to decrease
the resistance in series with the contacts. Thus the contactor and the
electronics package behaved as if the output impedance of the electronics
package decreased as the number of detectable electrical contacts increased.
Since the number of successful electrical contacts was always greater in
vacuum than in air, this apparent decrease in the electronics package's
output impedance may be partly responsible for the smaller average pulse
height when the contactor was in vacuum. Another possible explanation
is that the higher ambient temperature of the contactor in vacuum reduced
the contact forces by increasing the solenoid coil's resistance. This
lack of equality of pulse heights in vacuum and in air was not present
when the modified contactor was tested.

VI.1.1.8 Electrical Contact Data Taken in Vacuum Using the Modified
Contactor. Unlike the electrical contact data obtained using the original
contactor, the data obtained using the modified contactor is not presented
in the form of bar graphs enumerating the average height of the voltage
pulses observed on the recorder. Due to the highly repetitious nature of
most of the modified contactor data, sample data taken directly from the
recorder is presented. This permits the reader to observe the response of
the recorder when cold welding occurred.

Immediately after cleaning the contacts with alcohol and performing a final
checkout in air, the modified contactor was put in the vacuum system.
Within approximately 30 minutes after activating the vacuum system, the
internal pressure was below 10^{-6} torr. After 42 hours the pressure fell
to 1×10^{-8} torr. The total duration of the test was 49 hours.

During the first 5 hours of vacuum exposure the behavior of the new con-
tactor was very erratic. Data taken during this interval are shown in
Figures 25 through 27. Figure 26 shows the most erratic data of the
entire experiment. After about nineteen hours the data became regular and

Time   = 1 hour
Temp.   = 88°F
Pressure = 5×10^{-8} Torr
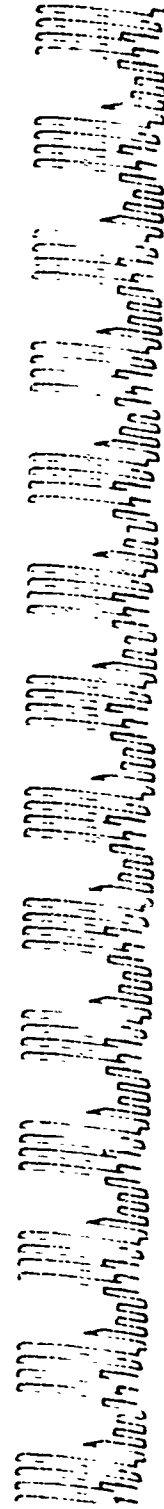
Figure 25   Electrical Contact Data Taken in Vacuum
Using the Modified Contactor
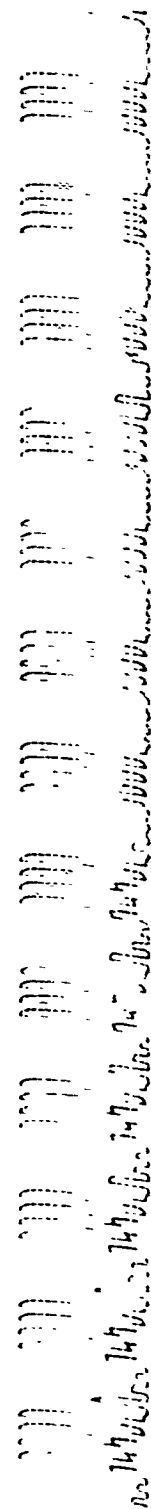
47

Time = 1-1/4 hours
Temp. = 230°F
Pressure = 5×10^{-8} Torr

Figure 26   Electrical Contact Data Taken in Vacuum
Using the Modified Contactor

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Time = 2-3/4 hours
Temp. = 88°F
Pressure = 3×10^{-8} Torr

Figure 27 Electrical Contact Data Taken in Vacuum Using the Modified Contactor

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Time   = 19.5 hours
Temp.   = 83°F
Pressure = 4×10^{-8} Torr

Figure 28 Electrical Contact Data Taken in Vacuum
Using the Modified Contactor

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Time = 35 hours
Temp. = 86°F
Pressure = 4×10^{-8} Torr

Figure 29 Electrical Contact Data Taken in Vacuum
Using the Modified Contactor
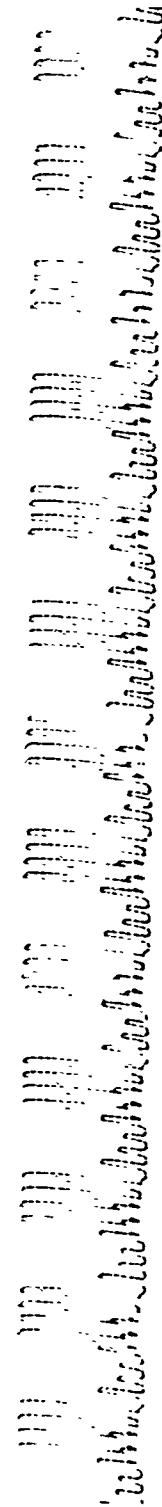
Time = 49 hours
Temp. = 82°F
Pressure = 1×10^{-8} Torr
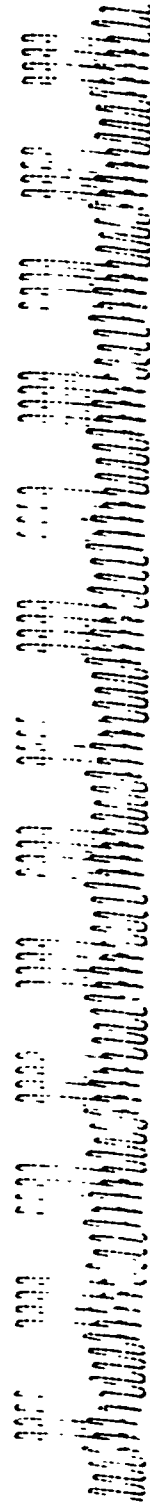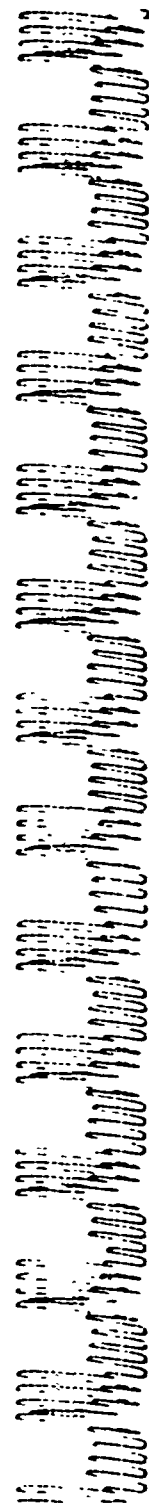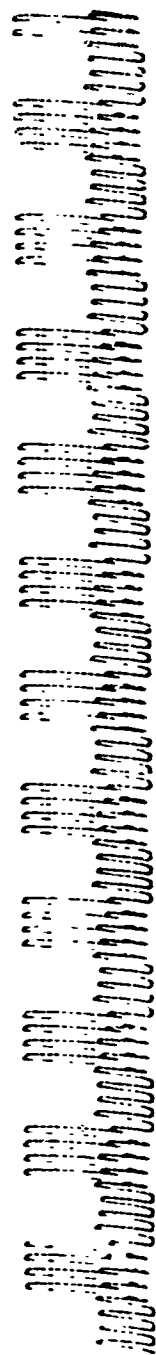
Figure 30 Electrical Contact Data Taken in Vacuum
Using the Modified Contactor

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One Minute After
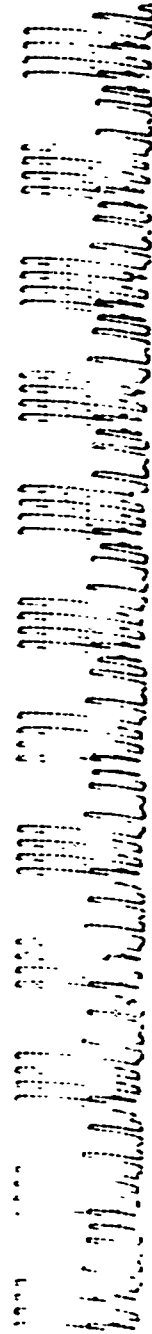Letting Vacuum
System Up To
Atmosphere

Figure 31   Electrical Contact Data Taken in Vacuum
Using the Modified Contactor

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repetitious during each actuation cycle (see Figure 28). This data
resembles the data obtained from the original contactor during its
vacuum test. After the data became regular, electrical contact was achieved
with almost 100 percent reliability. After 35 hours, intermittent cold
welding was observed at the copper-copper couple (see Figure 29). The
fact that the copper-copper couple had indeed welded together was confirmed
by observing the resistance across the appropriate electrical leads into
the vacuum system; there was less than one ohm resistance between the ends
of the leads attached to the copper-copper couple. The period during which
the intermittent cold welding of the copper-copper couple occurred lasted
for approximately ten minutes. Cold welding of the copper-copper couple
was not observed again after this period. Most of Figure 30 is a sample
of the very regular and repetitious data obtained throughout the remainder
of the test. It is interesting to observe the data as the vacuum system
was brought up to atmosphere; this data is shown in Figure 31.

VI.1.1.9 **Electrical Data Taken in the Vacuum and Ultraviolet Radiation**
Enviorments Using the Original Contactor. The data obtained during the
exposure to the combined vacuum and ultraviolet radiation environments is
normalized exactly like the original contactor data taken in the vacuum
environment (Paragraph VI.1.1.7). As in the case of the vacuum tests in
the absence of UV radiation, the pulse heights associated with successful
electrical contacts in vacuum were about 20 percent smaller than the
corresponding pulse heights observed when the contactor was in $70^{o}F$ air.
This irregularity is discussed in Paragraph VI.1.1.7, and did not appear
when the modified contactor was tested. The data are shown on Figure 32.
Throughout this test the pressure in the vacuum system remained between
1×10^{-7} and 1×10^{-8} torr. The contacts were initially cleaned with
alcohol. The duration of the test was 24 hours. No cold welding was
observed. In spite of the precautions discussed in Subsection V.4, the
temperature of the contactor rose from $80^{o}F$ to $108^{o}F$ during the 24-hour test.

The frequency of electrical contact was nearly 100 percent of the actuation
frequency. The contactor data, like the previous vacuum test data, showed
close reproducibility from cycle to cycle. Long term attenuation was more
severe than in the vacuum test without the UV radiation. The results
of previous tests in air at temperatures above $70^{o}F$ suggest that this
attenuation was due to the temperature rise of the contactor; after the
contactor had cooled down from $108^{o}F$ to approximately $85^{o}F$, the contactor
voltage signals rose to their previous values.

VI.1.1.10 **Electrical Data Taken in the Vacuum and Ultraviolet Radiation**
Environments Using the Modified Contactor. The data associated with this
test are shown in Figures 33 through 44. These data were taken directly
from the recorder (this permits the reader to observe when sticking
occurred). No cold welding was observed. The total duration of the test
was 74.1 hours; however, the ultraviolet lamp was not on continuously. The
pressure was always below 1×10 torr except during the first 1.1 hours
of the test. Electrical contact was achieved with almost 100 percent
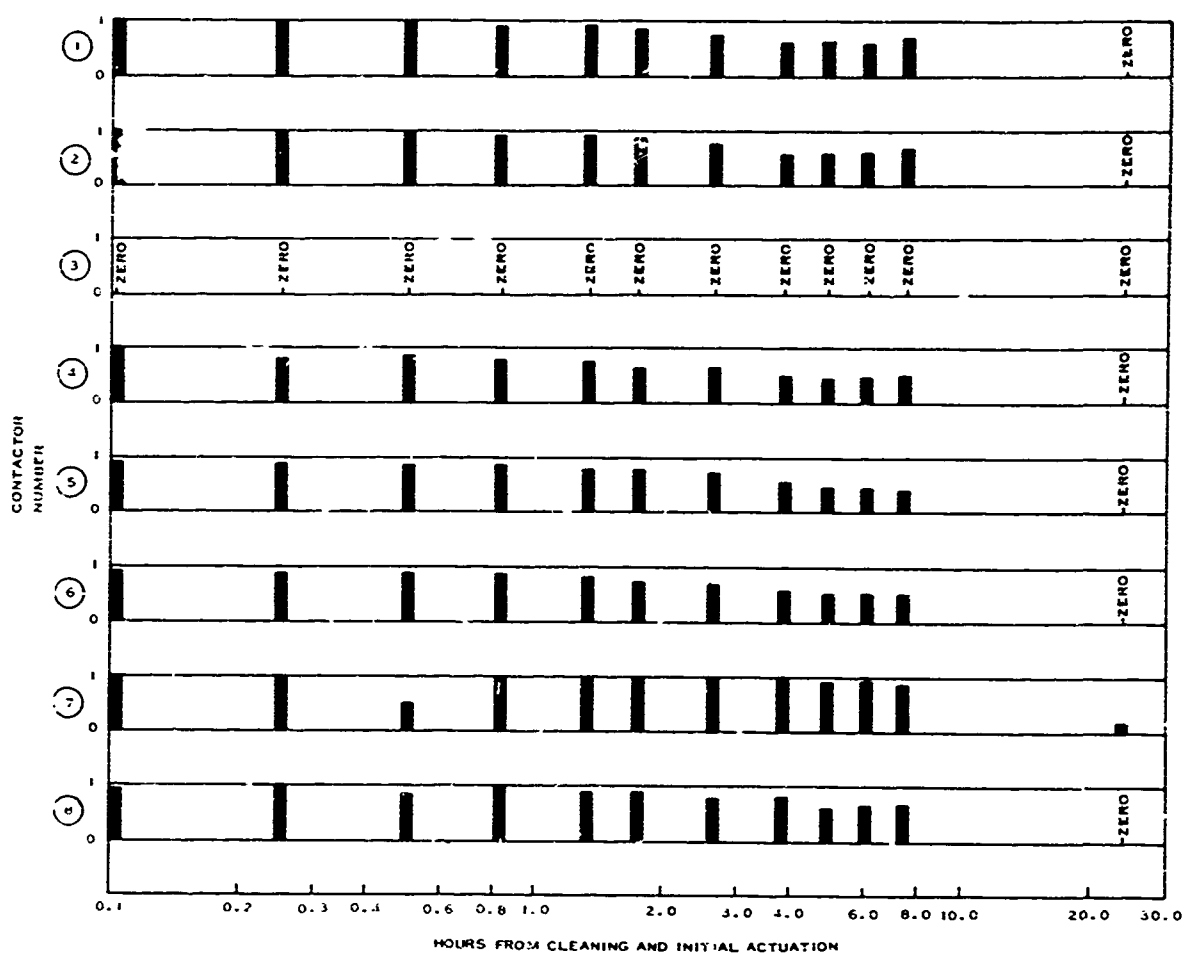reliability. The contacts were not cleaned with alcohol immediately

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Figure 32   Electrical Data Taken in Vacuum and Ultraviolet Environments
Using the Original Contactor

prior to the test; the data shown in Figure 33, which was taken at atmospheric pressure, indicates that cleaning the contacts was unnecessary.

Figure 33 shows the data which was obtained immediately prior to evacuating the vacuum chamber. Twenty-five minutes after the beginning of the test the recorded data adopted a regular pattern. Only contact No. 1 was not operational (see Figure 34). After 1.1 hours of operation all contacts were closing electrically (see Figure 35). At this time the ultraviolet lamp was turned on for one hour and five minutes. The record shown on Figure 36 was taken five minutes after the ultraviolet lamp was turned on, and is representative of all the data taken during this interval when the contactor was exposed to ultraviolet radiation. No immediate effects of the ultraviolet radiation can be observed. Figure 37 shows the data obtained immediately after the ultraviolet lamp was turned off. Note that the record pattern is almost identical to Figure 36. After the initial short exposure to ultraviolet radiation, the contactor was actuated for about sixty-four hours in vacuum in the absence of ultraviolet radiation. This prolonged exposure insured that the behavior of the contacts would be completely stable prior to determining if ultraviolet radiation could induce cold welding. Figures 38 through 40 are representative samples of the data taken during this sixty-four hour interval.

Sixty-seven hours after the beginning of the test, the ultraviolet lamp was turned on for 7.2 hours. Data taken during this interval is shown in Figures 41 and 43. There was a noticeable reduction in the average recorded voltage pulse heights during this period of ultraviolet exposure. This may have been due to a slight increase in the contactor's temperature. Definite sticking of the stainless steel and copper couple (Contact No. 8) is shown on Figures 43 and 44. There is no reason to associate this sticking with the presence of ultraviolet radiation since it clearly persisted after the ultraviolet lamp was turned off. The sticking may have been due exclusively to prolonged vacuum exposure. Since it was apparent that the ultraviolet radiation did not effect the contact resistance values of the contacts, the output of the AH-6 lamp was not calibrated.

VI.1.2 Camera Data and Discussion

Direct observation of the eight couples around the modified contactor was performed by motion picture photography at speeds of approximately 200, 800 and 2000 frames per second. The clearest and most useful scenes of the contactor's operation have been spliced onto a single reel of film which is being sent to the contract monitor under seperate cover. The individual contact numbers shown in the film differ from those shown in Table I according to the following table:

Film Numbering	1	2	3	4	5	6	7	8
Contact Number in Table I	1	8	7	6	5	4	3	2

In Air Immediately
Prior to Pumpdown
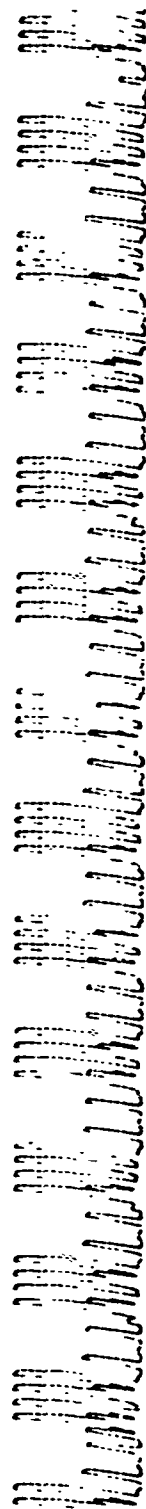Temp.   = 78°F
Pressure = 1 atm

Figure 33   Electrical Data Taken in Air Immediately
Prior to Pumpdown

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Time = 25 minutes
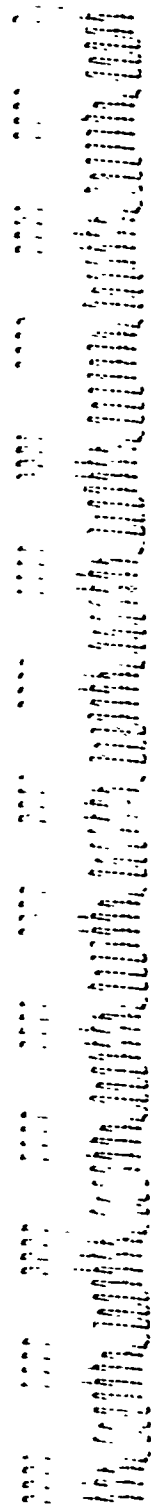Temp. = 77°F
Pressure = 1×10^{-6} Torr
Lamp OFF

Figure 34 Electrical Data Taken in the Vacuum and Ultraviolet Environment

Time = 1.1 hours
Temp. = 82°F
Pressure = 7×10^{-8} Torr
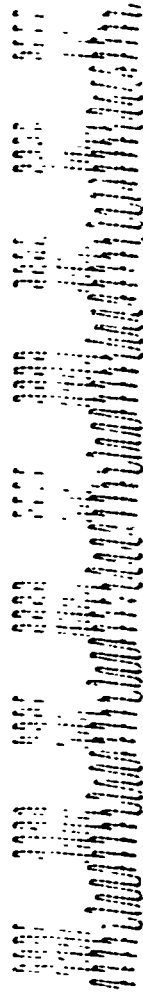Lamp OFF

Figure 35 Electrical Data Taken in the Vacuum and Ultraviolet Environment

59

Time   = 1.2 hours
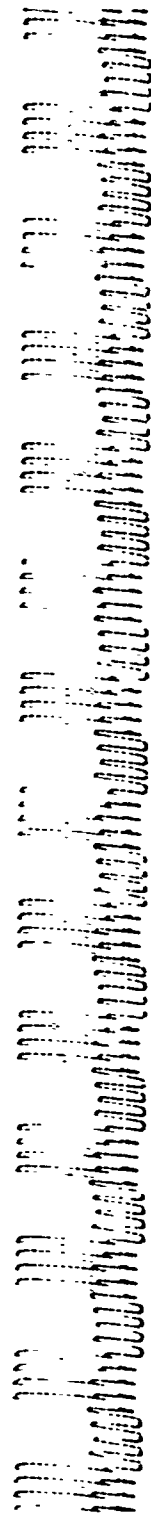Temp.   = 85°F
Pressure = 3 × 10^{-8} Torr
Lamp ON

Figure 36   Electrical Data Taken in the Vacuum and Ultraviolet Environment

Time = 2.3 hours
Temp. = 85°F
Pressure = 3 x 10⁻⁸ Torr
Lamp OFF
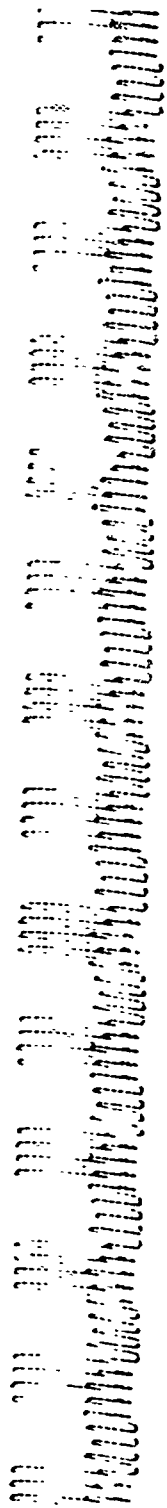
Figure 37   Electrical Data Taken in the Vacuum and Ultraviolet Environment.

61

Time = 24.5 hours
Temp. = 83°F
Pressure = 3×10^{-8} Torr
Lamp OFF

Figure 38 Electrical Data Taken in the Vacuum and Ultraviolet Environment

62

Time = 45.5 hours
Temp. = 81°F
Pressure = 3×10^{-6} Torr
Lamp OFF

Figure 39 Electrical Data Taken in the Vacuum and Ultraviolet Environment

63

Time = 66 hours
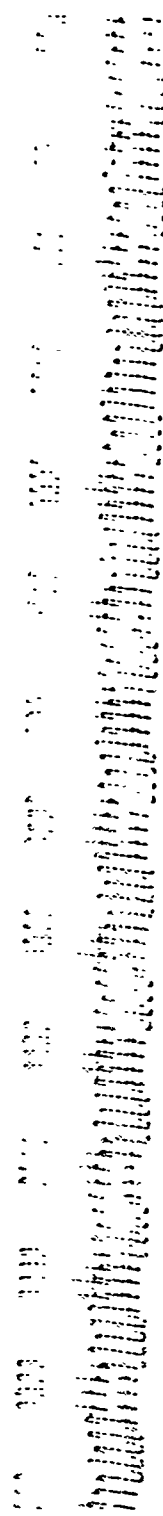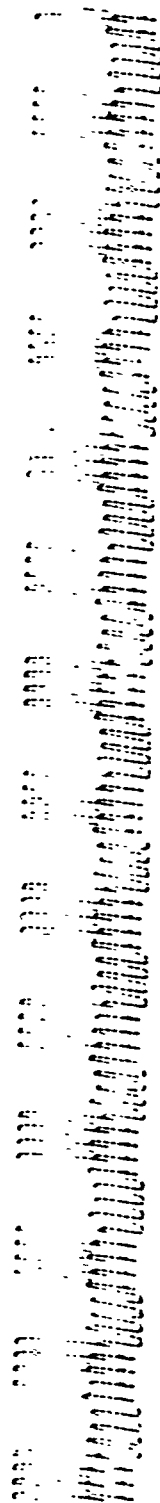Temp. = 80°F
Pressure = 1 x 10⁻⁸ Torr
Lamp OFF

Figure 40 Electrical Data Taken in the Vacuum and Ultraviolet Environment

64

Time = 67 hours
Temp. = 82°F
Pressure = 1 x 10⁻⁸ Torr
Lamp ON

Figure 41 Electrical Data Taken in the Vacuum and Ultraviolet Environment

65

Time = 73.8 hours
Temp. = 85°F
Pressure = 7×10^{-9} Torr
Lamp ON

Figure 42 Electrical Data Taken in the Vacuum and Ultraviolet Environment

66

Time = 74 hours
Temp. = 84°F
Pressure = 7×10^{-9} Torr
Lamp ON
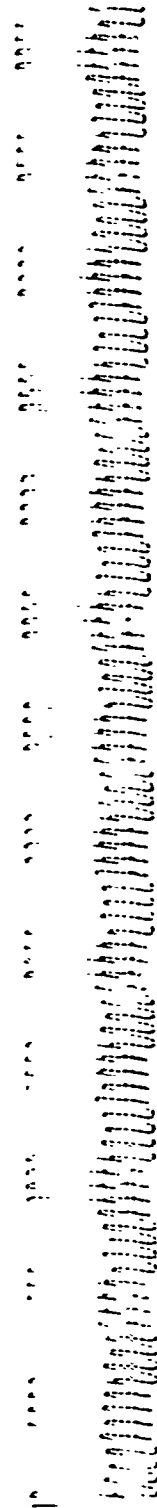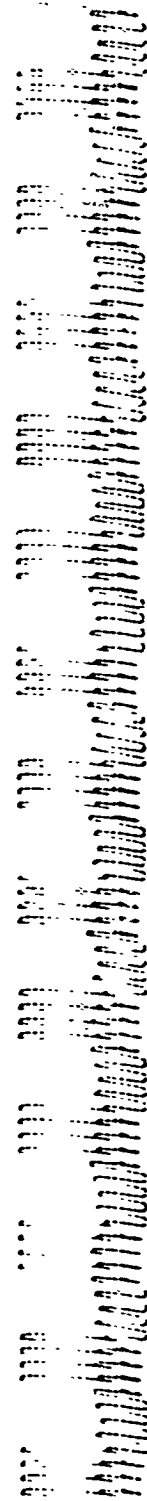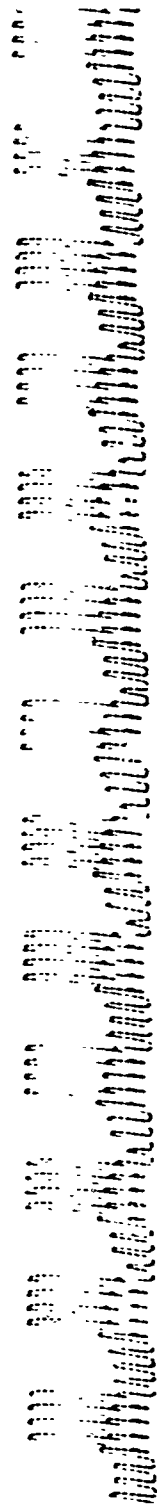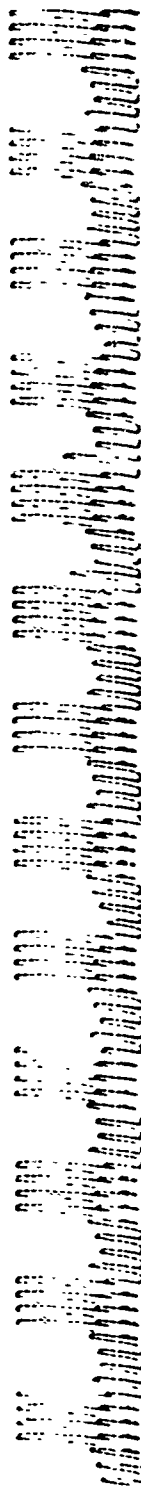
Figure 43   Electrical Data Taken in the Vacuum and Ultraviolet Environment

Time = 74.1 hours
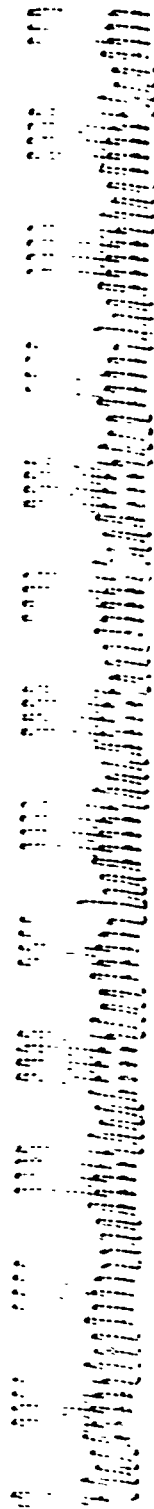Temp. = 84°F
Pressure = 7×10^{-9} Torr
Lamp OFF

Figure 44 Electrical Data Taken in the Vacuum and Ultraviolet Environment

A brief analytical study of the equations of motion of the contact system has indicated certain phases of the operation to watch for in the films:

a. Depending on the spring constant of the copper-beryllium beam spring and the mass of the ball and socket, the motion of the solenoid plunger will be transmitted to the contact ball mass with a characteristic vibration frequency superimposed;

b. After impact the vibration frequency is altered;

c. Repeated inelastic collisions damp out the vibrations.

The "backlash" effect of phase (a) can be clearly observed, especially in couple No. 6 (film No. 4). This effect complicates the determination of the impact velocity because the direction of motion is constantly reversing; it is even possible (although not observed in these films) for the velocity to be reversing at the moment of first impact. In general, the impulsive force is much greater than the static force (after rest) due to the beam spring pressure. It is also observed, with the spring constant inherent in this model of the supplemental contactor, that the moving balls never stop vibrating when the solenoid operation frequency is 158 actuations per minute.

VI.1.2.1 **Impact Velocities**. The knowledge of the impact velocities is required to calculate contact areas, contact pressures, and to determine whether deformations are occurring past the elastic stress regions of the contact materials. In general, the occurrence of cold welding is least probable at low stresses and increasingly more probable as plastic deformation is approached.

The gap distances of the contacts were determined directly from the film; this was possible since the actuator was initially at rest. The gap distances ranged from 0.0112 cm to 0.0411 cm; the velocity at impact was measured by determining the time of traversing the final 0.006 cm to 0.020 cm before impact. The point of impact could be viewed clearly under a microscope; the appropriate film frame was marked in the margin. Next, the number of frames backward in film time required for the contacts to separate a well-defined distance was determined. Resolution was generally ± 2 frames. A wire gauge 0.0198 ± 0.0005" in diameter was inserted between the pairs of contacts shown on the film, and this gauge was used to make the required distance measurements. Frame speed, calibrated against the strobe pulses in the film margin, varied between 0.000405 and 0.000432 sec/frame. Table III presents the results of the measured impact velocities.

TABLE III

FILM MEASURED IMPACT VELOCITIES

Couple No.	Materials	Impact Velocity	Uncertainty
1	S.S on S.S	5.5 cm/sec	± 1.7 cm/sec
2	WC on WC	7.5	± 2.8
3	Al on Al	3.8	± 0.9
4	Cu on Cu	4.8	± 1.4
5	S.S on Al	7.2	± 2.7
6	S.S. on Cu	4.2	± 2.6
7	S.S. on Al	5.6	± 1.3
8	S.S. on Cu	5.5	± 1.7

The overall value of the camera data, besides the determination of approximate impact velocities, lies in its clear visual presentation of the actuation dynamics. Future designs of this type of contactor may wish to incorporate changes such as increased beam spring stiffness, gap separation uniformity, and alignment correction provisions. When cold welding does occur, such improvements would permit a more precise enumeration of the corresponding conditions.

VI.2 ANALYTICAL RESULTS AND DISCUSSIONS

The theoretical analysis of Section IV is presented in eight graphs (Figures 45 to 52) showing contact pressure and area vs. impact velocity. Again it must be stressed that the plotted curves are only valid in the elastic region of velocities. The extension of this data beyond the dashed vertical line only indicates minimum transition region velocities, since the true curve is known to diverge downward. As noted previously, the extent of this divergence cannot be calculated by any available theory. Elastic limits are indicated against the pressure axis. The onset of the plastic region, with the attendent limitations and uncertainties as discussed in Section IV, is also indicated against the pressure axis. The cross-sectional contact area is calculated on the basis of perfect spherical contacts, or equivalently, for new balls on their initial impact. The operating range of each couple, determined from the camera data, is indicated against the impact velocity axis.

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Figure 45 Average Pressure and Contact Area Vs. Impact Velocity (Stainless Steel)

Figure 46 Average Pressure and Contact Area Vs Impact Velocity (Tungsten Carbide)

Figure 47 Average Pressure and Contact Area Vs Impact Velocity (2014 Aluminum)

73
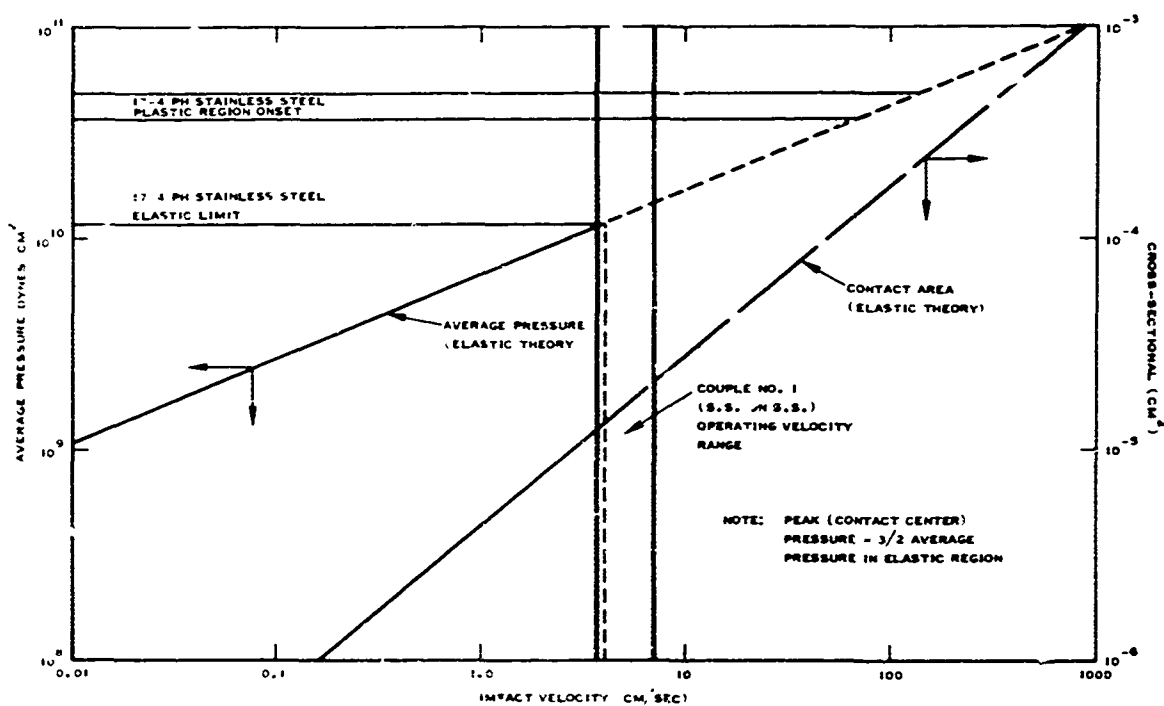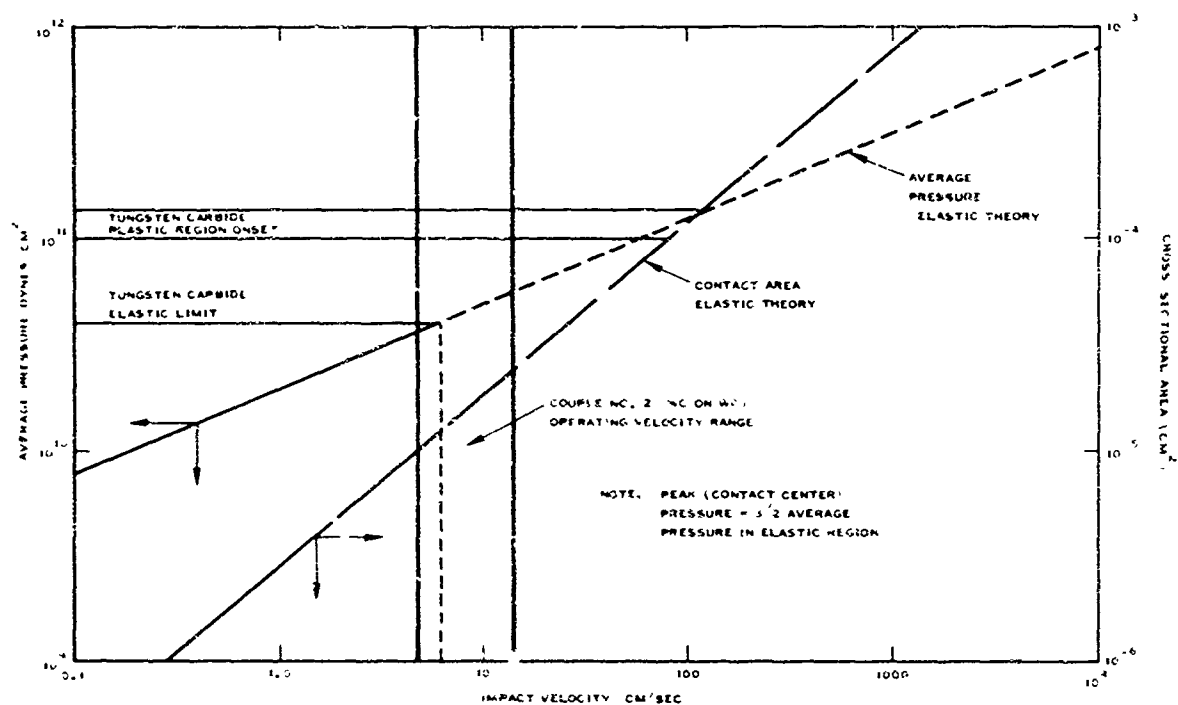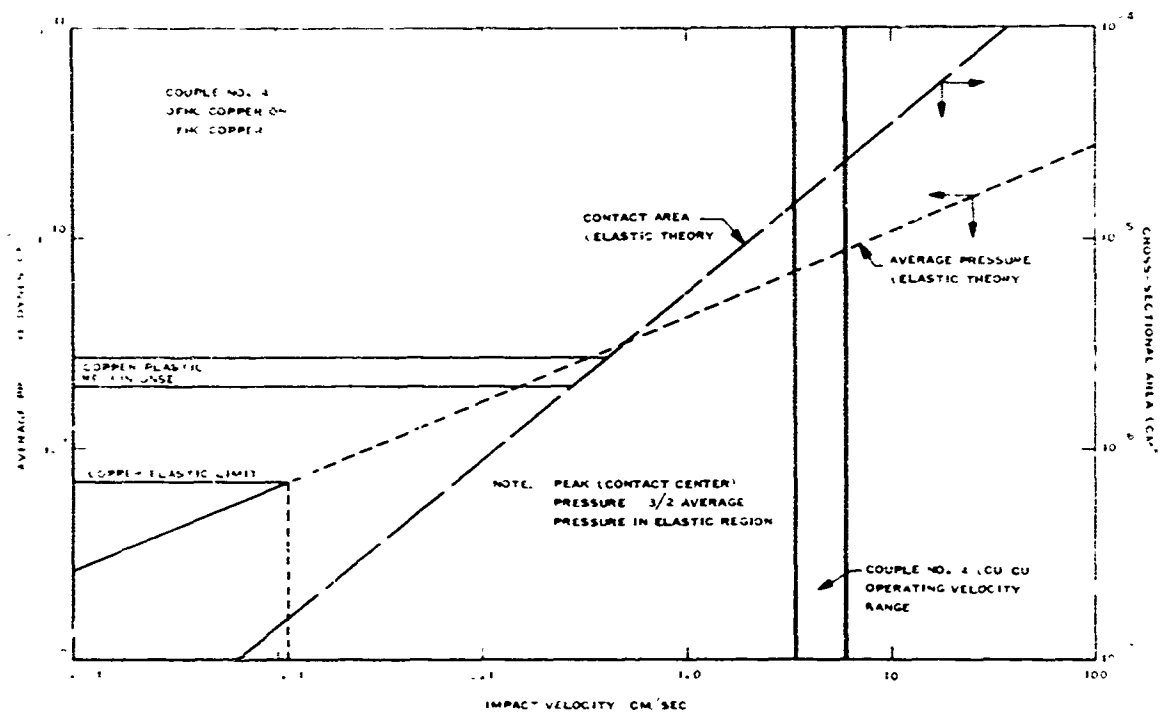
Figure 48 Average Pressure and Contact Area Vs. Impact Velocity (OFHC Copper

Figure 49 Average Pressure and Contact Area Vs. Impact Velocity
(440 Stainless Steel on 2014 Aluminum)

Figure 50 Average Pressure and Contact Area Vs Impact Velocity
(440 Stainless Steel on Copper)

76

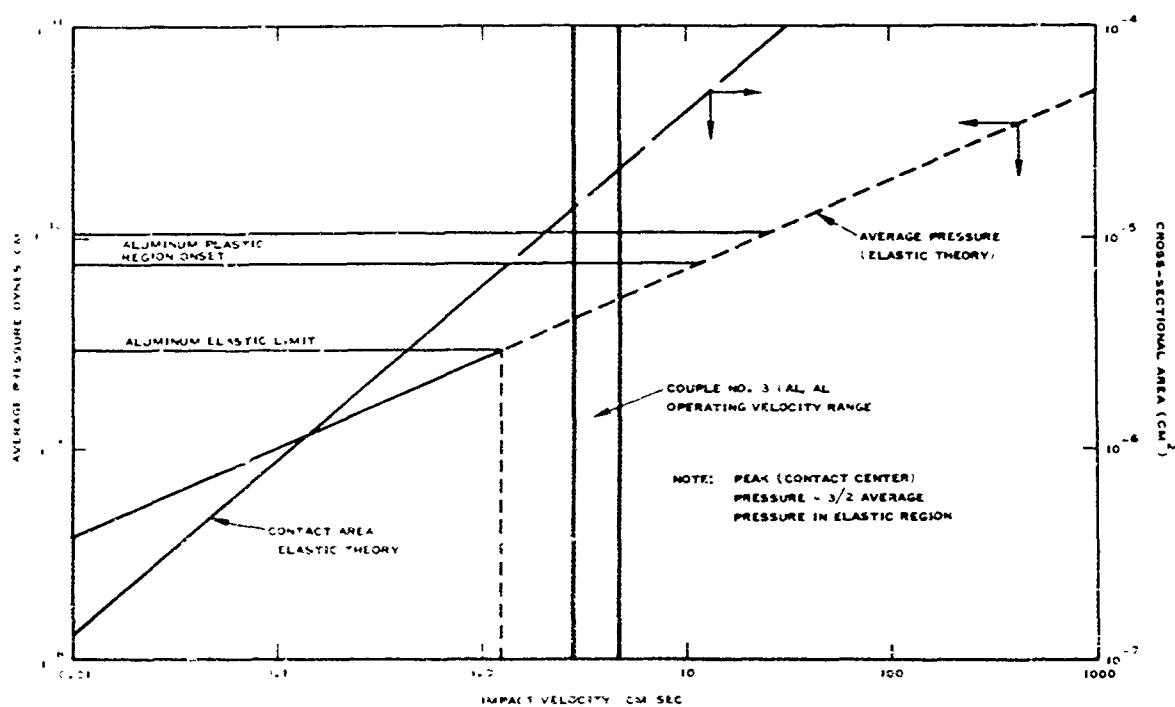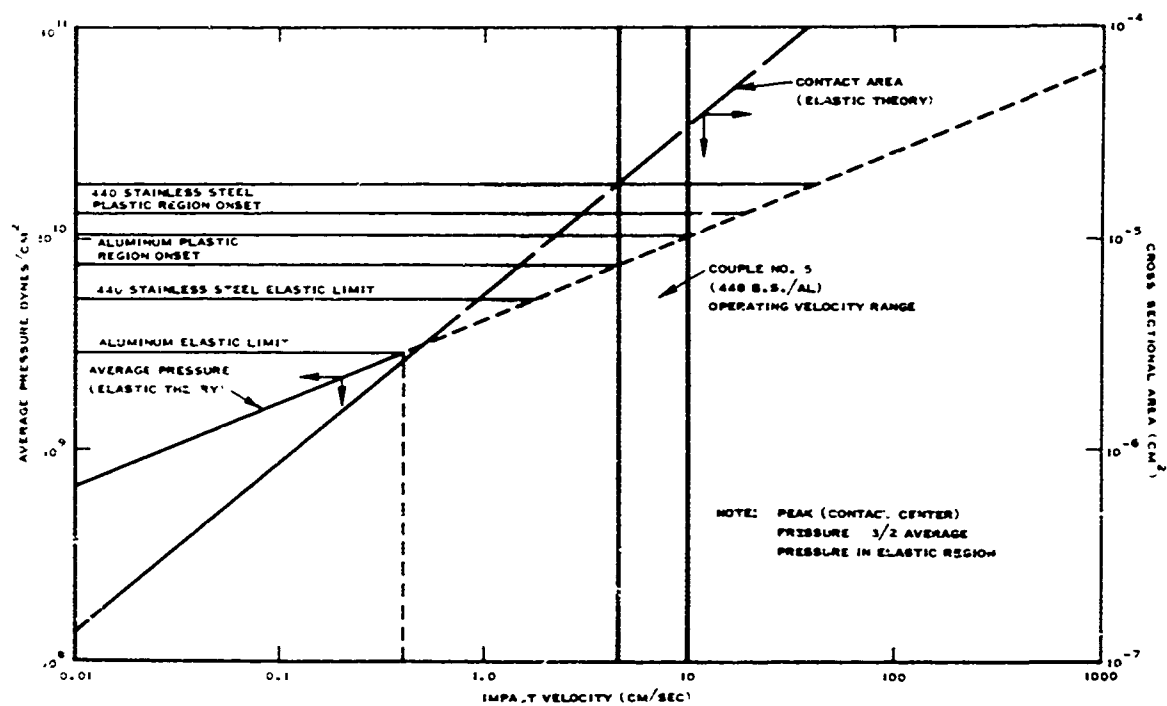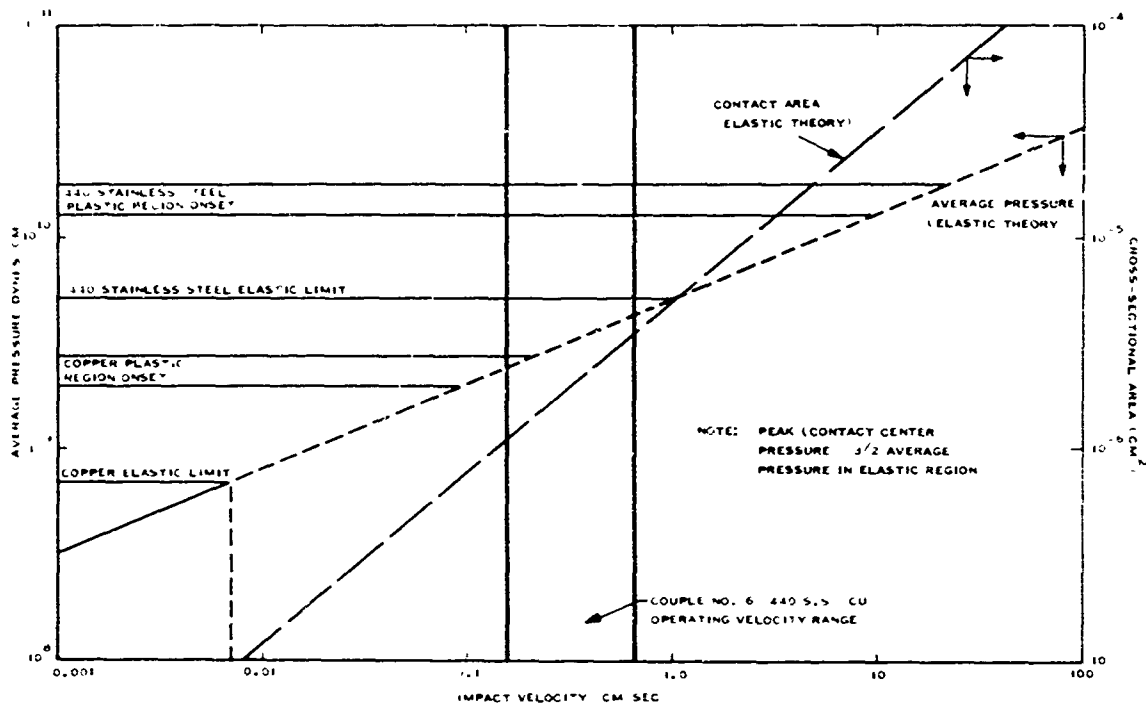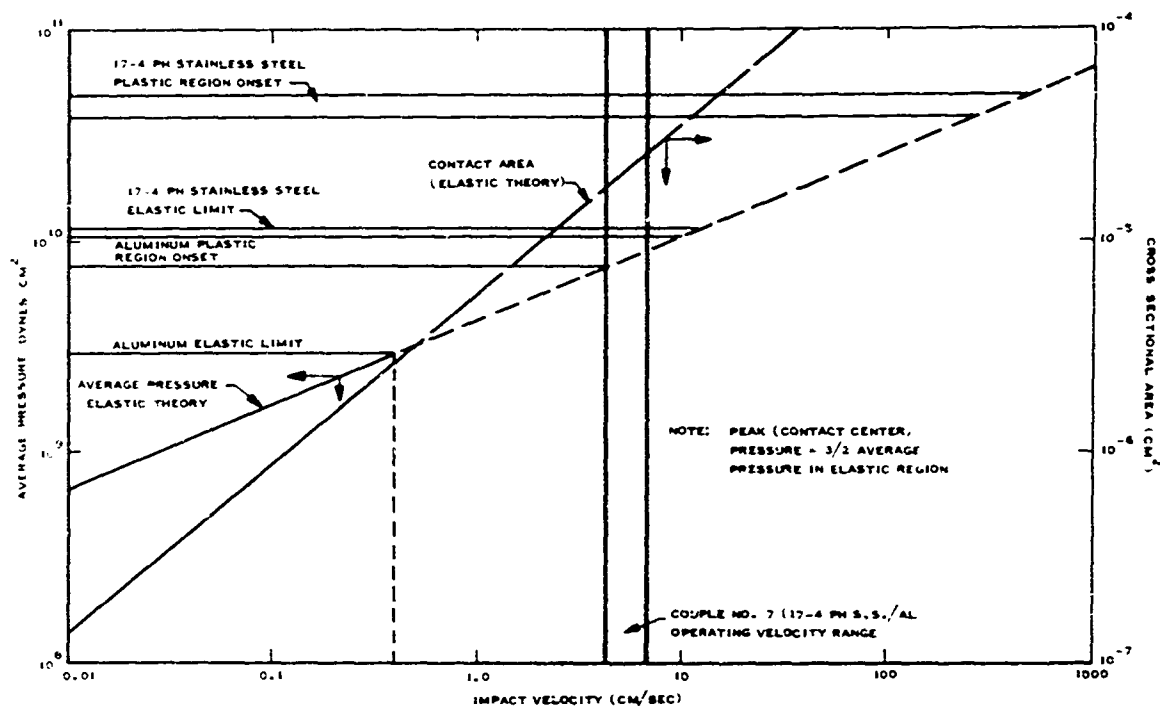Figure 51   Average Pressure and Contact Area Vs. Impact Velocity
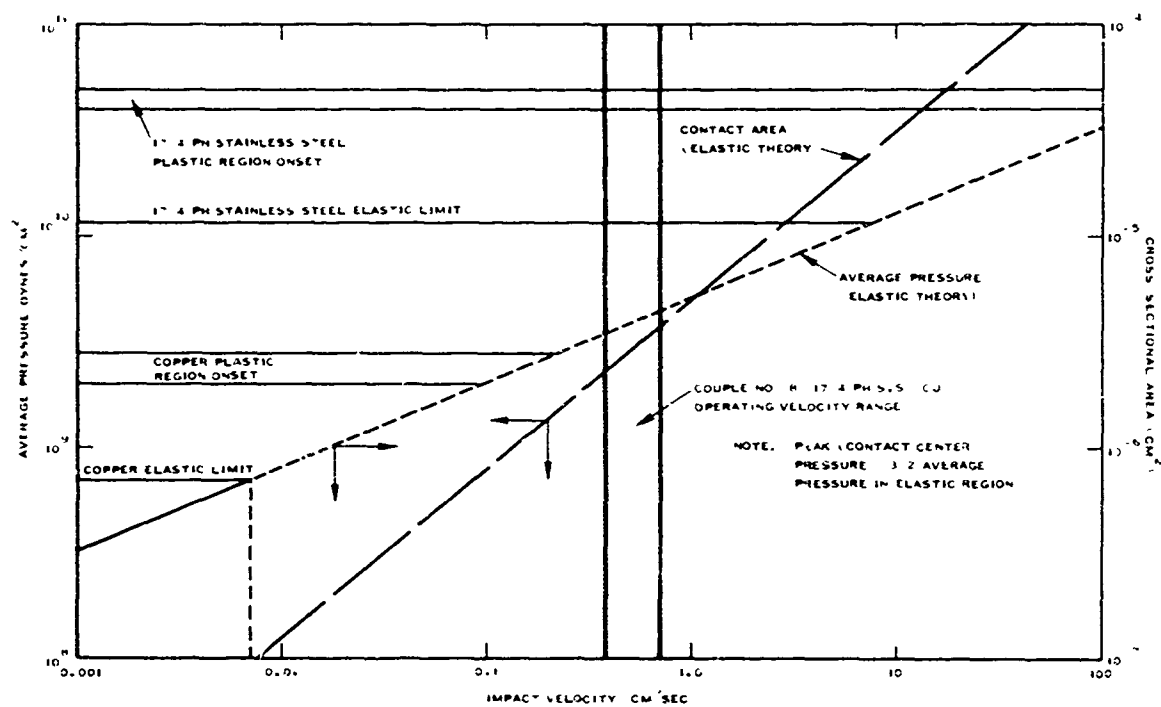(17-4PH Stainless Steel on Aluminum)

77

Figure 52 Average Pressure and Contact Area Vs. Impact Velocity
(17-4PH Stainless Steel on Copper)

These graphs are intended to indicate only the fact that the operating velocities produce impacts either inside or outisde the elastic strain limits of the coupled materials.

It is observed that, with the possible exception of contacts No. 1 and No. 2, all collisions are beyond the elastic limit of at least one of the contact materials. Contacts No. 1 and No. 2, tungsten carbide on tungsten carbide and stainless on stainless, overlap the elastic limit velocity in their uncertainty range but are most likely beyond it. The contact with the highest probability of experiencing cold welding is seen to be contact No. 4, copper on copper, where the impact velocity is nearly three orders of magnitude greater than the elastic limit velocity. Next in probability appear to be aluminum on aluminum and 440 stainless on aluminum (which may be complicated by aluminum surface conditions), and tungsten carbide on tungsten carbide and 17-4PH stainless on stainless.

To some extent, we should acknowledge the possibility of a "self-healing" effect in repeated operations. If a new pair of bails initially impacts beyond the elastic limit, some permanent deformation may occur. This increases the contact area, and the force of subsequent impacts will be spread over a larger area (thus reducing the average pressure). In the limit of many cycles we might expect a pressure/deformation "equilibrium" near the elastic limit point. Most certainly we could disassemble the contactor and measure the diameter of any flattened region on the balls; this has not been done to date since we may still desire to take additional data with the modified contactor. The modified contactor cannot be re-assembled because the spring is spot-welded to the contactor body.

In conclusion, it appears that the results of the theoretical analysis are in agreement with the observed cold welding effects. One instance of cold welding and one instance of adhesion were observed while testing the modified contactor in vacuum. In each case copper, the metal which was strained furthest beyond its elastic limit, was involved.

SECTION VII

OUTLINE OF CONCLUSIONS AND RECOMMENDATIONS

This section presents a concise outline of the conclusions, results, and recommendations generated by Philco-Ford during the Phase I effort on this contract.

VII.1 CONTACTOR PERFORMANCE

A. It is concluded that the impulsive stress levels of all eight couples at the measured solenoid impact velocities were sufficiently high to induce adhesion and cold welding.

   1. Proved experimentally for copper.

   2. Justified analytically if ball not flattened.

B. The balls flatten during use.

   1. Proved by visual observation.

   2. Justified analytically; plastic deformation occurs.

C. There exists a backlash effect in the contactor spring.

D. Previous electrical contact data may contain systematic errors due to the fact that some of the balls were loose in their sockets and there was a lack of rigid mechanical and electrical contact between the copper-beryllium spring and the main body of the contactor.

E. The contacts are not influenced by ultraviolet radiation.

F. The measured values of the resistance of the contacts are strongly dependent on temperature above approximately $100^{\circ}F$.

VII.2 ADVANTAGES AND DISADVANTAGES OF THE TECHNIQUES EMPLOYED DURING THE PRESENT EXPERIMENT

A. The vacuum pumps (ion, sublimation, and cryogenic) employed during the present work maintained an environment in which the frequency of electrical contact was nearly 100 percent of the contactor frequency. The frequency of successful electrical contact in a diffusion-pumped system was substantially lower (Ref. 1).

B. The pressure of 10^{-8} torr used in the present experiment appears
    to be sufficiently low to induce cold welding, but a lower
    pressure might increase the probability of adhesion or cold
    welding.

C. In order to simulate a mission profile using ground simulation
    equipment, it is important to incorporate the anticipated
    temperature changes of the contactor.

D. A high contactor actuation frequency was employed during the
    present work in order to increase the probability of observing
    cold welding during the rather limited testing periods
    available. The disadvantage of this procedure is that the
    movable ball is not at rest prior to each actuation stroke.
    Future tests should utilize a slower actuation frequency with
    longer test periods, or a stiffer spring constant with
    appropriately adjusted gap distances and solenoid velocities.

E. During the present work the initial curvature of the balls was
    not measured. It is important to obtain this information in
    order to determine the initial stress levels due to impact.
    Further, in order to take into consideration any variation in
    the stress levels due to increased flattening resulting from
    continued actuation, it would be necessary to determine the
    rate of flattening of the contacts as a function of the
    contactor total actuation count.

VII.3 RESULTS OF PHASE I EXPERIMENT

A. One occurrence of cold welding was observed: copper on copper.

B. One occurrence of adhesion was observed: stainless steel on
    copper.

VII.4 RECOMMENDED SUPPLEMENTAL CONTACTOR DESIGN MODIFICATIONS

A. Weld the copper-beryllium spring directly to the main body
    of the contactor to insure good electrical contact and align-
    ment between the stationary and non-stationary balls.

B. The supporting structure of the stationary balls should be made
    of aluminum oxide rather than boron nitride. This would
    prevent the deterioration of the screw threads noted in
    Section III.1.

C. It is desirable, although admittedly difficult, to introduce
    thermocouples to monitor the temperature of the contacts during
    operation.

VII.5 RECOMMENDED ADDITION .. CONTACTOR TESTS

A. In vacuum (pressure less than 10^{-8} torr) in the temperature range $72^{O}F$ to $200^{O}F$.

B. Determine stress levels as a function of contactor total actuation count.

1. Determine rate of flattening of balls.

C. Estimate when, in terms of contactor total actuation count, cold welding is not likely to occur.

1. Incorporate flattening rate of balls.

2. Determine analytically the amount of flattening required to get inside elastic limit.

VII.6 DATA INTERPRETATION

Based on the experimental data and the accompanying analyses, the following hypotheses can be advanced: cold welding will not occur inside the elastic limit if an oxide layer is present on the surfaces.

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13. ABSTRACT

The purpose of this research was to (1) study the behavior of contact resistance in air and in vacuum, and (2) determine if the stress levels on a small experimental contactor were sufficient to induce cold welding in vacuum. In each case the following metals were considered: aluminum, copper, stainless steel, and tungsten carbide. The experimental contactor is described in AFRPL Report No. AFRPL-TR-67-1 (DDC Document No. AD 380181). The experimental results show that an ion-pumped vacuum system can be successfully employed to remove physically absorbed contaminants which would otherwise lower the probability of successful electrical contact. By analyzing high-speed motion pictures, and employing the theory of elastic deformation, it was shown that the impact forces of the contacts were high enough to deform the substrate which supports the surface oxide layer. The copper on copper contact was observed to cold weld in vacuum. Adhesion of the stainless steel and copper contact was also observed in vacuum.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cold Welding						
Electrical Contact Resistance						
Vacuum Welding						
Space Environmental Effects						